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VOLUME II

MANUFACTURING METHODS AND TECHNOLOGY FOR ELECTROMAGNETIC COMPONENTS

PHASE II

Prepared for: U.S. Army Missile Command
Redstone Arsenal, AL 35809

AEROSPACE GROUPS

HUGHES

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CULVER CITY, CALIFORNIA

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Various techniques for the manufacture of low cost, high reliability core type transformers/inductors for missile system applications were investigated and evaluated. A typical missile VC core high voltage inductor and toroidal core high voltage transformer were selected as representative test items. Molding technologies ranged from silicone or "slush" molds for low quantities (100's/month), individually pressurizable hard molds (1000's/ month), to liquid injection mold (LIM) with transfer presses (10,000/month). (continued on back)		

19. Continued

Core banding
 Fine magnet wire joining
 Magnet wire stripping
 Transformer molding

Silicone molds
 Liquid injection molding (LIM)
 Wire insulation damage detector

20. Continued

Over 40 encapsulation thermo setting compounds for high reliability components were tested and evaluated. Two compounds were selected, one optimum for low stress applications, the other for high voltage, corona free applications. Cure times are main limitation of production rates, pointing up a need for faster cure time materials of at least an order of magnitude.

Winding techniques included establishing parameters for damage of fine wire windings on square bobbins, and a method of continuously monitoring insulation integrity of magnet wire during winding operations for both toroid, and bobbin/stick winders. Use of spot bonding instead of mylar tape to hold windings in place during the winding operation was developed to eliminate voids caused by the tape during encapsulation/potting.

Using a centrifuge for 5 to 10 minutes to remove bubbles from a poured transformer, then curing at room pressure showed promise over the conventional pressure cure at 500 psi for the required cure time and temperature.

High voltage gradient estimation and control to achieve corona-free encapsulation was investigated. Various methods of establishing conductive surfaces for faraday shielding of molded bobbins were evaluated. Molds for casting void free bobbins were made. Various methods of terminating fine (AWG 36-44) and ultra fine (AWG 45-56) wire in coils to intermediate AWG 36 leads were investigated, including soldering with conventional tin-lead, and tin free solders, laser welding, crimping, conductive adhesives, etc.

A method of discharge welding of "C" core bands under tension, without clips, to achieve a low profile, and eliminate solder creepage was demonstrated.

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FOREWORD

This is Volume II of a two-volume set covering the work done October 1979-October 1980 in investigating, evaluating and implementing techniques for the manufacture of low cost, high reliability magnetic components for missile system applications. The Executive Summary, Conclusions and Recommendations, and the Work Statement are in Volume I, but covers this volume also. Each volume has its own Table of Contents, Lists of Illustrations and Tables, references and appendices. In addition, this volume has cost data estimates and implementation efforts to date.

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7.0 INTRODUCTION

This document, consisting of Volumes I and II, covers the effort to investigate, evaluate, and implement techniques for the manufacture of low cost, highly reliable electromagnetic components for missile systems applications. The Phase I effort, Volume I, concentrated on improving the manufacturing methods of potting, encapsulation, and winding of electromagnetic devices. Volume II, the follow-on phase, designated as Phase II, had the objective to investigate interconnection techniques, tooling and structural parts. Implementation of the combined results of Phase I and Phase II will hopefully improve manufacturing methods for electromagnetic components so that a significant pay back in manufacture and life cycle costs of missile systems due to lower production costs, higher process yield, and improved reliability will be obtained. The information to be obtained will also contribute to the manufacturing of certain types of electromagnetic devices with significantly reduced sizes and weights which will further reduce the cost of the missile systems.

The "implementation" part of this project during the Phase I effort was the dissemination of information to accomplish the above objectives to those vendors who are manufacturing magnetic components for missile systems on an "as you go" basis rather than waiting until the project is completed. This approach had two definite advantages. First, and most obvious is that the earlier such information becomes available, the sooner it can be incorporated into the manufacturing processes and the beneficial results obtained. The second and not so obvious result is that contact with the vendors during the course of the project resulted in a useful dialogue between the MM&T project

personnel and the vendors allowing an exchange of information on their problem areas and other considerations, resulting in increased understanding of the overall problems involved.

A list of attendees and the program at the debriefing held 28 October 1980, at Hughes Aircraft Co., Culver City, is given in Table 12-1, of this volume.

8.0 INTERCONNECTION TECHNIQUES

Five different areas were covered in this task, namely: stripping of wire insulation, techniques for joining ultra fine coil wires to intermediate lead wires, size requirements for intermediate leads, radii of connections as a function of operating voltage, and methods of making low cost reliable connections in high voltage components.

8.1 STRIPPING OF WIRE INSULATION

Five methods of insulation removal from electrical conductors in industry are:

1. Thermal
2. Abrasive
3. Chemical
4. Air-abrasive
5. Laser

All of these were considered for insulation removal from fine and ultrafine wire. Of these five categories, the last three were investigated in depth for their applicability to fine wire. The results of the investigation of all of these categories is reported below.

8.1.1 Thermal

Probably the most used method of insulation removal from wire is the application of heat, either by a soldering iron or flame, to insulation materials. Some insulation systems are designed for removal with soldering iron with the melted insulation material serving as a flux for the soldering operation.

These include "solder-thru" polyurethane, trade name Sodereze^(TM), one insulation system — a polyurethane with a nylon overcoat — is strippable by a soldering iron at 750°F. The problem of solder strippable insulation in the fine and ultrafine wire sizes is that during this operation and subsequent tinning dissolution of the copper by the tin in the solder is a serious problem.

Insulation systems which require higher temperatures for removal than available with a soldering iron or the decomposition products do not enhance the tinning of the wire are usually removed by a flame method. At one vendor, this was accomplished by using a paper match for each stripping operation, the rationale being that a paper match is more or less a constant temperature flame. The match was scratched and used for each insulation removal operation. Other sources of flame used are butane or liquid fuel cigarette lighters. After exposure to the flame, the insulation is removed manually by stroking the wire with a small piece of fine abrasive paper, which removes the insulation and cleans the wire surface preparatory for tinning.

One problem in this method of insulation removal which has not been addressed is the effect of the momentary high temperature altering the annealing of the wire. This would be especially true in the fine wire because of the much smaller thermal mass which does not carry away the heat applied rapidly, as is the case with larger wire sizes. It would appear that investigation of the change in metallurgy of the wire as a function of wire gauge for given temperature of flame would be useful information to determine the effects of this method of insulation removal.

8.1.2 Abrasive

Removal of wire insulation by rubbing or stroking with fine abrasive paper is a common method, especially for wire insulation systems designed for very high temperatures, for example 200°C.

Wire stripping machines are commercially available which consist of counter-rotating soft abrasive cones or cylinders, where the spacing between can be adjusted to accommodate the size of wire. These appear reasonably effective for the larger wire sizes which can be rotated in the fingers and the

degree of insulation removal observed. Manufacturers' data on one machine specified that it would remove insulation from wire sizes up to AWG 50. The ends of straight, short lengths of fine wire can be stripped successfully using this machine because the wires can be rolled by the fingers during the stripping operation. It requires appreciable manual dexterity to strip fine wires which are part of a bobbin or toroidal winding to achieve the same degree of completeness of insulation removal. A disadvantage of this equipment is that the spinning abrasive wheels put a strain on the wire, tend to pull it into the machine, and care must be taken by the operator to prevent contact of the winding itself with the rotating abrasive wheels.

In all these methods of removal of insulation from fine magnet wires using a flame or abrasive action to break the insulation material away from the conductor by mechanical means was heavily dependent upon operator dexterity. The resulting variations of the electrical and strength properties of the conductor in these operator-dependent processes cannot be adequately controlled. However, in the absence of better methods, industry accepts their use.

8.1.3 Chemical

Softening and/or removal of wire insulation by chemical means is employed with some high temperature insulation systems which are considered difficult to remove by other means. Two chemical stripping compounds used during this investigation were Lonco 504, HMS 20-1699 Type I(A), and Ambion Insulstrip, HMS 20-1699 Type III(A). The wires (insulation) tested were:

JW 1177/12, Type H2 (polyester-imide or polyester-amide-imide),
AWG 50

JW 1177/14, Type K2 (insulation overcoated with polyamide-imide),
AWG 50

JW 1177/15, Type M (Polyimide, overcoated with polyamide-imide),
AWG 36

JW 1177/15, Type M2 (Polyimide, overcoated with polyamide-imide),
AWG 20

The chemical stripping compounds were tested utilizing two Teflon boards fabricated with a grid of channels on the top surface as shown in Figure 8-1. These boards were positioned and held in place on a slightly

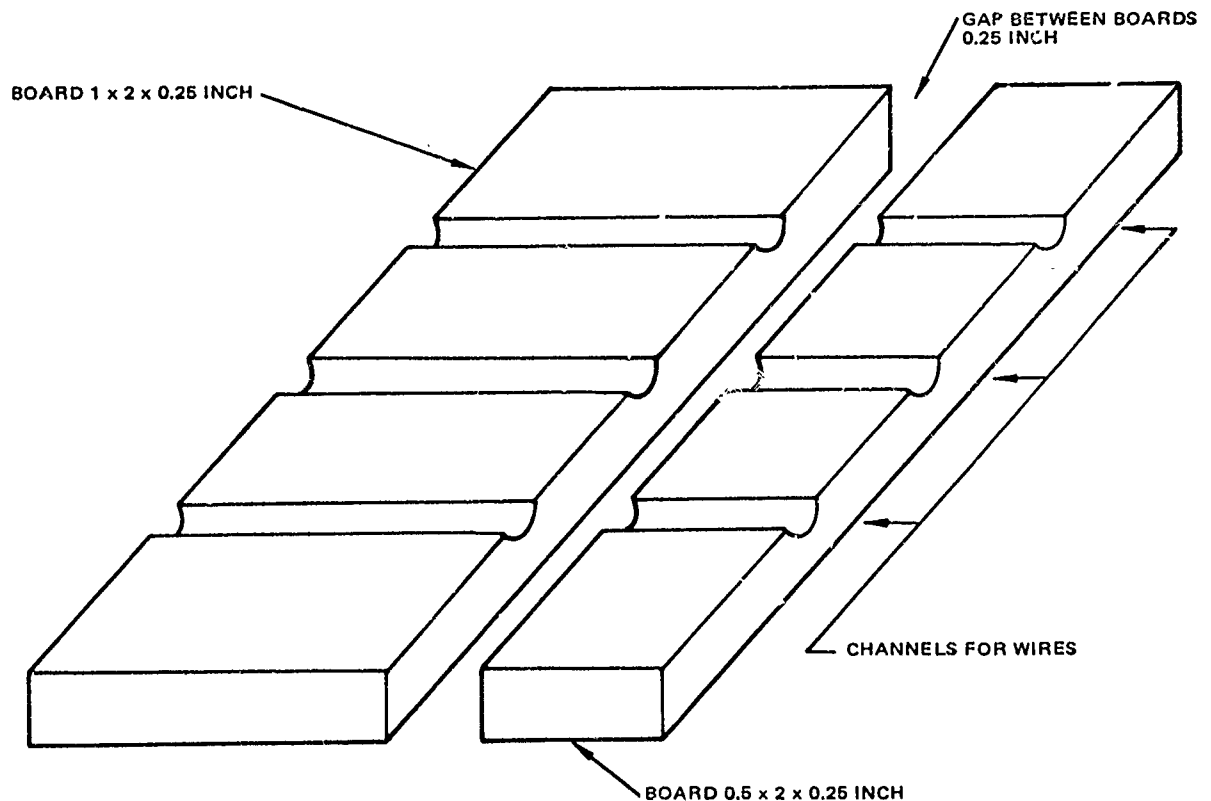


Figure 8-1. Fixture for chemical wire stripping.

larger metal block using clamps. About 3-inch long sections of the wires were placed in the channels and secured to the support block at both ends. Droplets of the stripping compound were applied in the channels of the wider board and the spread of the liquid promoted using a glass rod. The wires were then rinsed with distilled water and isopropyl alcohol dispensed from squeeze bottles while the metal support block was held in such a way that the wires were in a near vertical position. This way the stripping compound was rinsed away from the top section of the wires where the connected magnetic part may be secured in an actual operation.

Evaluation of the tests was restricted to the visual monitoring of the flow of the stripping and the rinsing fluids using 7X magnification. The Arabian Insulstrip (HMS 20-1699 Type III) is effective with the JW 1177/11 insulations but such wires were not available. It was assumed that, for the observation of the general handling and wetting conditions, this incompatibility

could be disregarded. The same approach was taken when the JW 1177/14 and /15 wires were used as specimens for the tests (the compatible stripping compound, HMS 20-1699, Type II is not applicable to the processing conditions).

Visual evaluation of the tests for the application of the chemical stripping compounds showed no evidence of contamination on the wire surface adjacent to the section where the magnetic parts would be placed. The AWG 20 wire, because of the large diameter, extended above the level of the board and the stripping material did not cover the top surface of the specimen. The results of the application of chemical stripping compounds showed that this method is suitable for use on lead wires of magnetic parts.

The controlled use of the method requires proper tooling for the separation and individual treatment of the wires attached to the same part. Care must be taken to prevent splashing onto the coil, such as a protective shield or bay enclosure. The corrosiveness of the chemicals may be a problem, especially if neutralization is required. Complete removal by appropriate cleaning steps is necessary as the compatibility of residual chemical with the encapsulants is not usually known; what is known, is that curing of some insulation systems is inhibited by presence of certain classes of chemicals.

8.1.4 Air-Abrasive

The use of small abrasive particles propelled by an air blast to remove insulation was investigated in depth. A preliminary test was performed using a brass rod wrapped in DuPont Kapton to simulate ML insulated wire. A commercially available abrasive equipment removed the Kapton from the brass rod in a very effective manner.

Several samples of actual wire were stripped using the air-abrasive equipment. Figures 8-2 and 8-3 are photographs of insulation removed from AWG 20 gauge wire and AWG 32 gauge wire stripped in an identical manner, respectively. Both of the wires were relatively easy to hold and strip by hand. Figure 8-4 is a photograph of a piece of AWG 42 wire stripped with abrasive. This wire could not be held free-hand and stripped so a piece of hard rubber with a "Vee" groove cut into its surface with a razor blade was used. The wire was laid in the groove for support. The operation was not

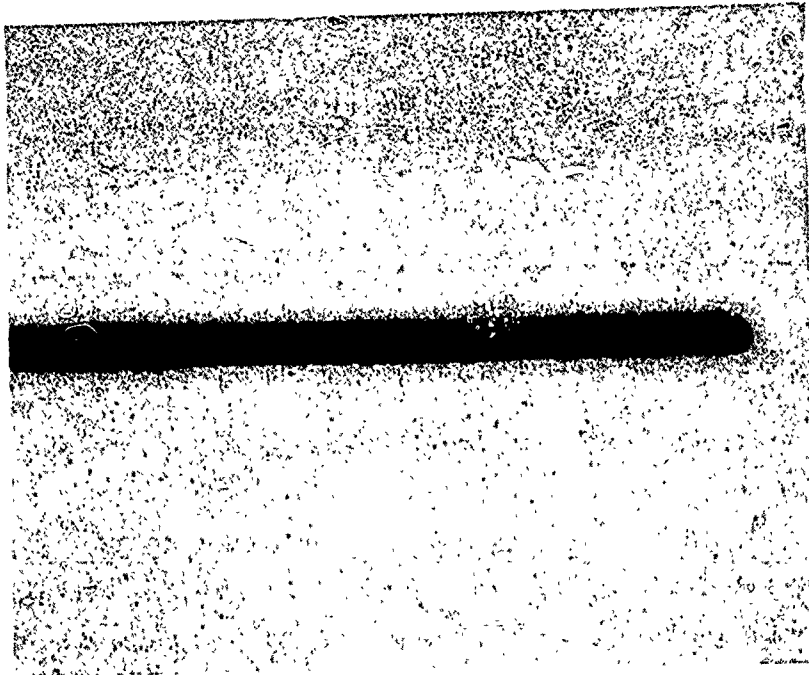


Figure 8-2. 20 AWG (dia. 0.032 inch) copper magnet wire ML insulation; air abrasive stripped.

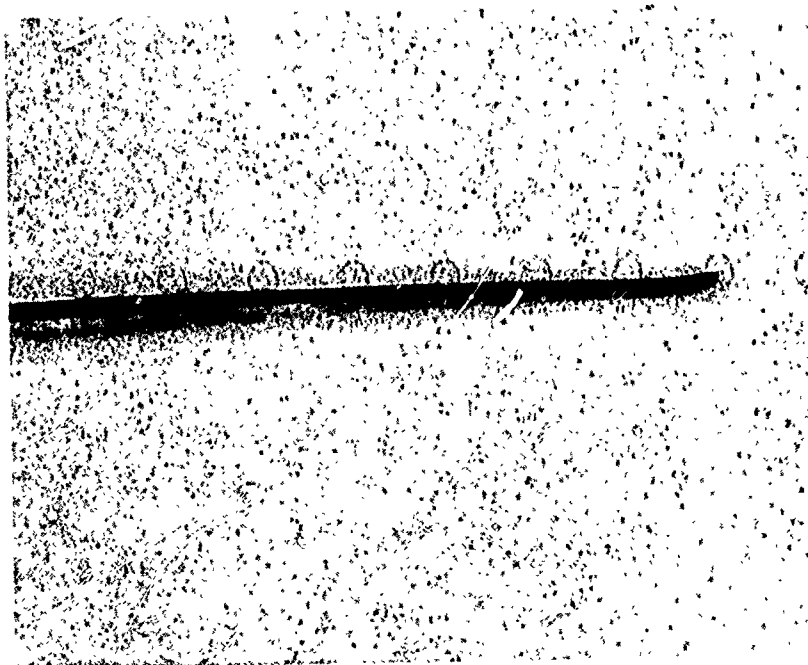


Figure 8-3. 32 AV/G (dia. 0.008 inch) copper magnet wire ML insulation; air abrasive stripped.

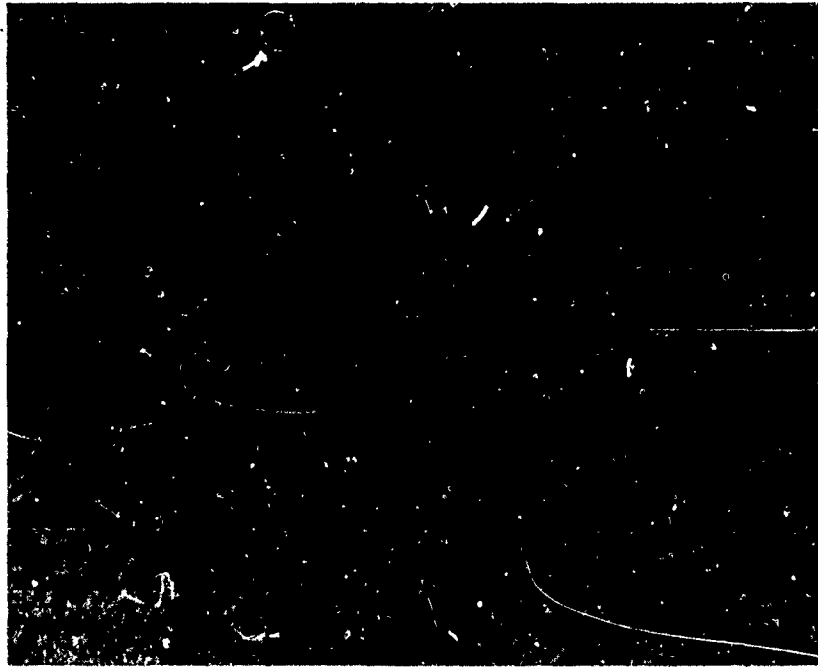


Figure 8-4. 42 gage copper magnet wire ML insulation air abrasive stripped upper wire insulated, lower wire stripped. Wire dia. 0.0025 inch.

easily accomplished because the wire insisted on curling which lifted it out of the groove. After considerable effort, the wire was stripped. Obviously, the Vee groove approach is not feasible for a production system.

Figure 8-5 is a photograph of AWG 52 wire which has been stripped along side some AWG 52 unstripped wire for comparison. The methods used to strip this wire were so laborious and clumsy that further stripping by hand was not considered practical.

On the basis of initial results with a hand-held abrasive nozzle, it was decided that some form of tooling would be necessary for stripping fine wire. The air blast caused the wire to whip in an uncontrolled manner and also caused it to curl. The curl was assessed initially as caused by the force of the air blast and the removal of insulation on one side resulting in a stress unbalance. A nozzle was designed and fabricated as drawn in Figure 8-6. Four angled holes lead from an annular plenum chamber, which is supplied with a mixture of high pressure air and abrasive into a central hole for the wire.

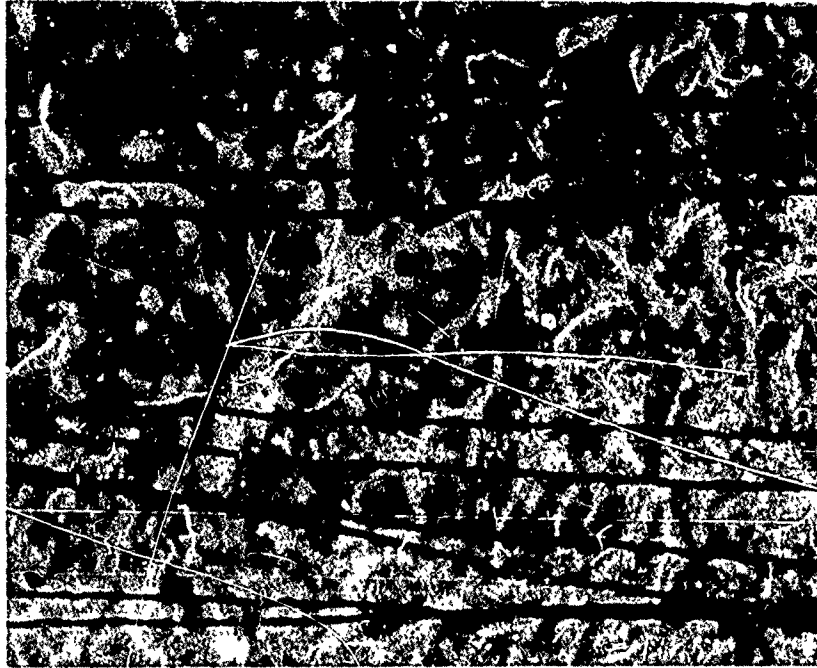


Figure 8-5. 52 gage copper magnet wire type T insulation air abrasive stripped upper wire insulated, lower wire stripped. Wire dia. 0.00088 inches.

The flow of the mixture aspirates air into one end and ejects air and abrasive from the other end. The aspirated air pulls the wire to be stripped into the hole and the four jets keep the wire centered in the flow of abrasive.

During actual tests, it was found that the wire would curl and wedge along the side of the main hole between the abrasive inlet holes. Obviously, some forces existed which overcame the planned centering effect of the air flow. The wire was observed to be stripped only on one side.

A new nozzle was designed and fabricated, to overcome these problems as drawn in Figure 8-7. Instead of four holes to direct the air and abrasive mixture against the wire, a continuous aperture was used with the air in a swirling motion so that the abrasive particles would impinge the wire from all sides. The aperture was adjustable to regulate the air abrasive mixture available for stripping. Tests showed that the swirling action resulted in the fine wire being coiled up like a coiled spring while the insulation was being removed. Elimination of the swirling action stopped the

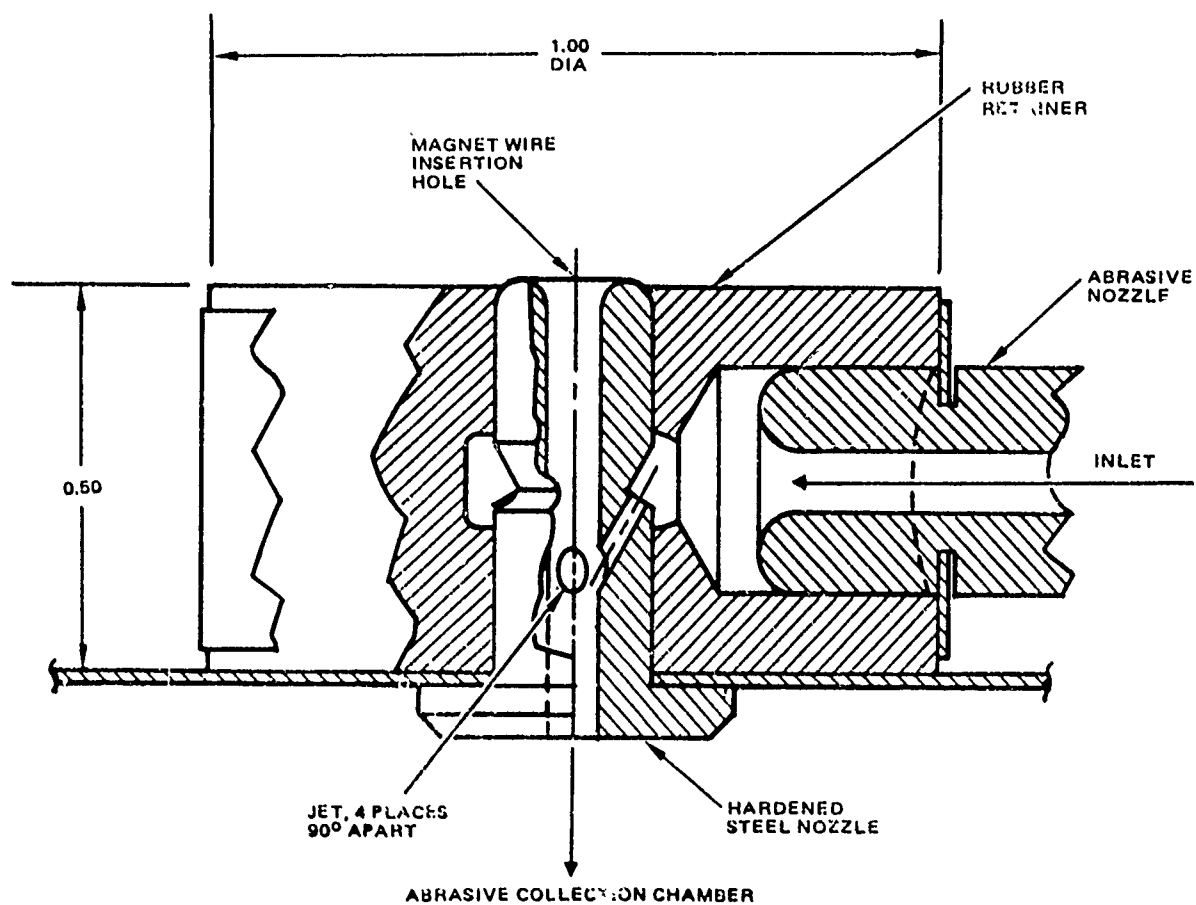


Figure 8-6. Four jet nozzle.

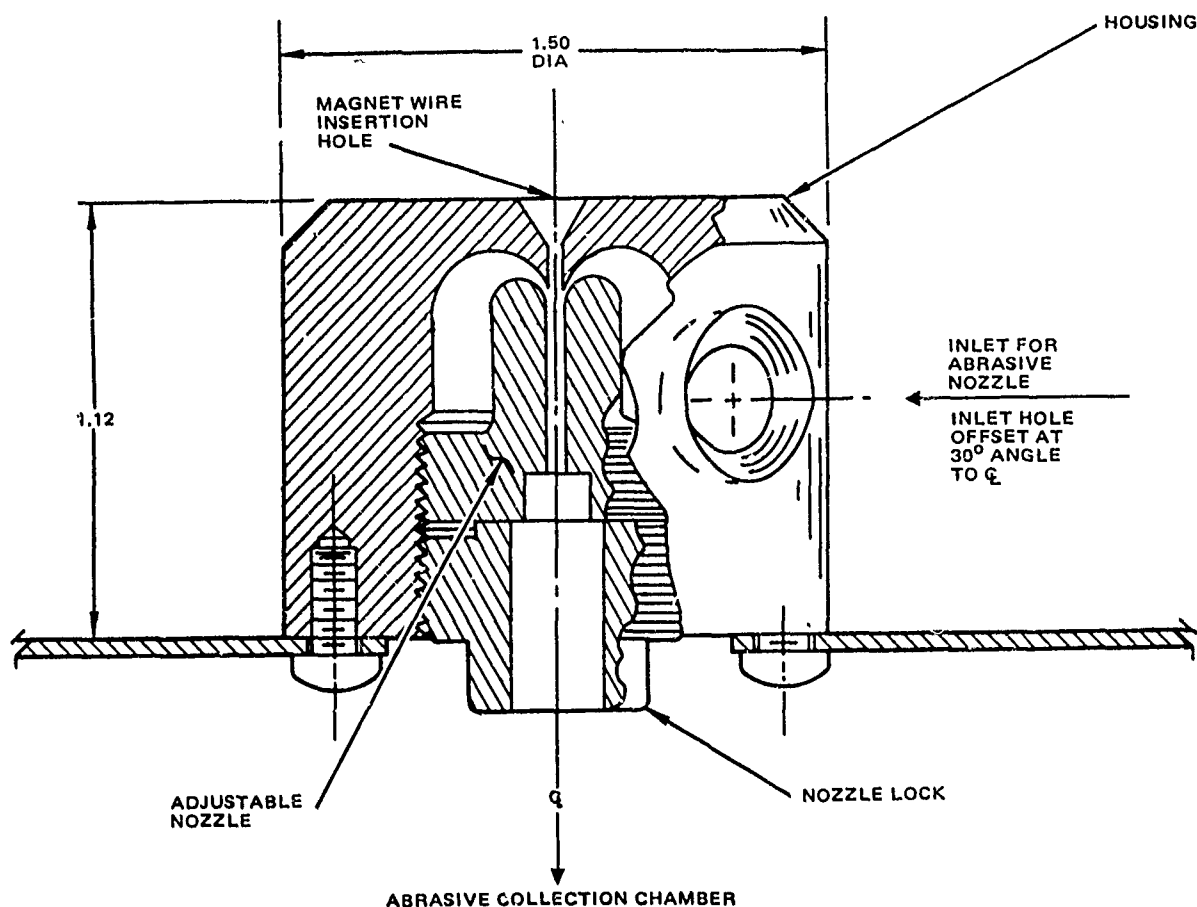


Figure 8-7. Continuous jet adjustable nozzle.

tendency of the wire to coil up, but it would still curve. It was found that the insulation was removed with little or no erosion of the copper itself.

After successful stripping of the wire subsequent attempts to solder or tin the wire were not successful. It had been assumed that the air abrasive action would provide a frosted, clean wire surface which should accomplish both the insulation removal and cleaning, but such was not the case. At this point in time, a company was found and contacted which had expertise in the use of air-abrasive equipment to remove insulation from wire (Secana Co., Appendix 16.2h). The following information was obtained, based on their work on stripping fine insulated resistance wire used in wire-wound potentiometers.

Their findings and recommendations were as follows:

- a. The abrasive particles act as shot, similar to a commercial process known as shot peening for surface hardening to strengthen highly stressed steel parts. The high velocity abrasive work hardens the surface of the copper wire. Because it is not being done instantaneously on the entire surface of the wire, one side becomes work-hardened, resulting in a curl of the wire.
- b. Alumina abrasive material will result in a wire surface which is impossible to solder in a satisfactory manner.
- c. Pharmaceutical grade sodium bicarbonate used as an abrasive will produce abraded wire that can be satisfactorily soldered. Apparently, commercial grades have enough foreign filler or contaminants so that a clean surface is not obtained and the wire cannot be soldered.
- d. A special orifice plate must be employed to use the bicarbonate of soda in commercially available air abrasive units.
- e. A right angle nozzle cannot be used with sodium bicarbonate abrasive, as apparently, it will not turn a corner. It packs and cuts off the flow where an abrupt change in direction is encountered.
- f. Each type of abrasive material has a critical air pressure below which it will not cut or abrade. This critical pressure produces a very abrupt cut or no cut condition. Excessive air pressure will result in wire damage even without the presence of abrasive.
- g. Each substance to be abraded requires a specific abrasive. A list of typical abrasive materials is as follows:

Silicon carbide
Alumina
Glass balls
Dolomite
Bicarbonate of soda
Talc
Corn starch

After finding that sodium bicarbonate is the only known substance to date that will produce a solderable surface on copper wire, also that it is reluctant to turn corners, and is hygroscopic (absorbing moisture from the air) which causes it to cake, the design of a suitable nozzle to achieve stripping of insulation from fine and ultrafine wires would require more effort and resources than are practical at this point.

An additional problem which needs to be considered in this approach is the possibility of abrasive particles becoming lodged into the coil winding itself. It seems to be almost impossible to mask the coil body, and the effects of the particles on the encapsulation system and possible effect on the insulating properties would also have to be considered.

8.1.5 Laser

Wire stripping tests were made using a carbon dioxide laser operated at 2 to 2.5 watts power and in the 10.2 to 10.6 micrometer (μm) wavelength range. The 0.13-inch diameter beam was focused through a 1-inch focal length lens to 0.00673 inch. Power distribution (calculated) was 100 kW/in^2 at the perimeter. The focusing lens was attached to the back side of a nozzle-like device that allowed the purging of the focal area with a stream of oxygen gas applied at 1 psi valve pressure.

The wires (insulation) tested were:

JW 1177/21, Type H2 (polyester-imide or polyester-amide-imide),
AWG 40

JW 1177/14, Type K2 (insulation overcoated with polyamide-imide),
AWG 30

JW 1177/15, Type M (polyimide, overcoated with polyamide-imide),
AWG 36

JW 1177/15, Type M2 (polyimide, overcoated with polyamide-imide),
AWG 20

Samples of these wires were held in the beam by clamps and also manually; there was no equipment available for the controlled movement (rotation, lateral shifts, timing) of the specimens.

Small sections (approximately 0.25 inch long) of the wires were exposed to the focused laser beam and to the flow of the oxygen for approximately one minute. Attempts to manually rotate the specimens for complete stripping were not successful because of the narrowness of the beam and the unsteady nature of the manual positioning.

The wire specimens exposed to the laser beam were submitted for testing using Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray Analysis (EDAX).

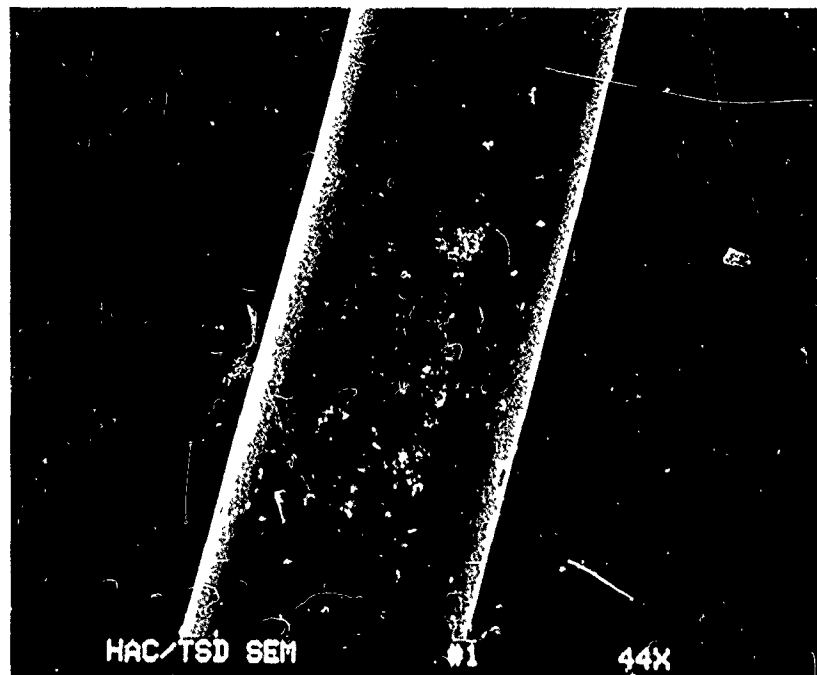
The SEM analysis of the specimens showed evidence of varying degrees of insulation removal by the laser exposure, with the exception of the AWG 20 (JW 1177/15 Type M2) wire. The diameter of this latter wire is 0.040 inch and the effect of the exposure is visible in the form of bubbling of the insulation and the distinct path of the beam in the (approximate) center of the surface as shown in Figure 8-8. There is, however, no EDAX evidence for the presence of copper on the surface.

Satisfactory removal of the insulation is shown for the AWG 40 (JW 1177/12 Type H2, 0.003 inch diameter) wire, Figure 8-9. The EDAX shows the presence of copper. The two remaining specimens evidence the effect of the laser exposure but surfaces of the conductors are partially contaminated with the residue (debris) of the insulation as shown in Figures 8-10 and 8-11. The surface of the JW 1177/14, Type K2 (AWG 30) specimen showed the presence of titanium in addition to copper.

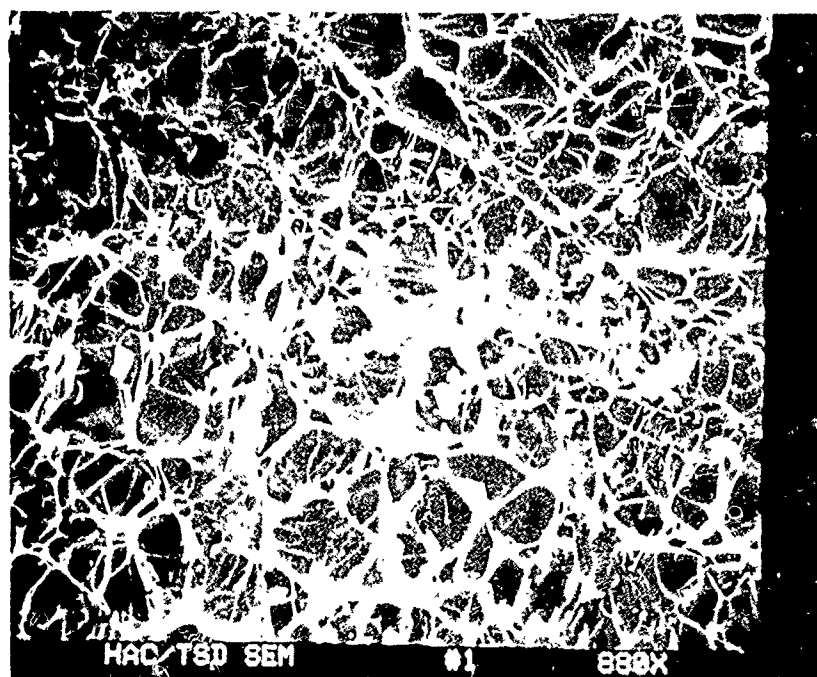
The results of the tests using the energy of the carbon dioxide laser for the removal of the insulation show that the principle of this technology, first worked out (see Reference 14.7) for stranded conductors, is applicable to the processing of magnetic components. It is also evident that the facilities available for this work were not adequate to provide sufficient data to initiate the use of laser stripping on the fabrication level.

The following recommendations are given for the continued development of the laser application for insulation removal:

1. Controlled, mechanical positioning is needed to hold the wire steadily in the focal point of the laser beam.
2. Optical-mechanical devices are needed to direct the movement of the laser beam on a spiral path around the wire to assure that the entire area to be stripped is exposed for the minimum time required.
3. The nozzle for the gas purge must allow the gas flow to reach the area to be stripped simultaneously with the laser exposure.
4. The solderability of the stripped conductor need to confirm the absence of adverse effects from the laser exposure.



a. 44X magnification



b. 800X magnification

Figure 8-8. Effect of laser exposure on JW 1177/15, type M2 wire, AWG 20.

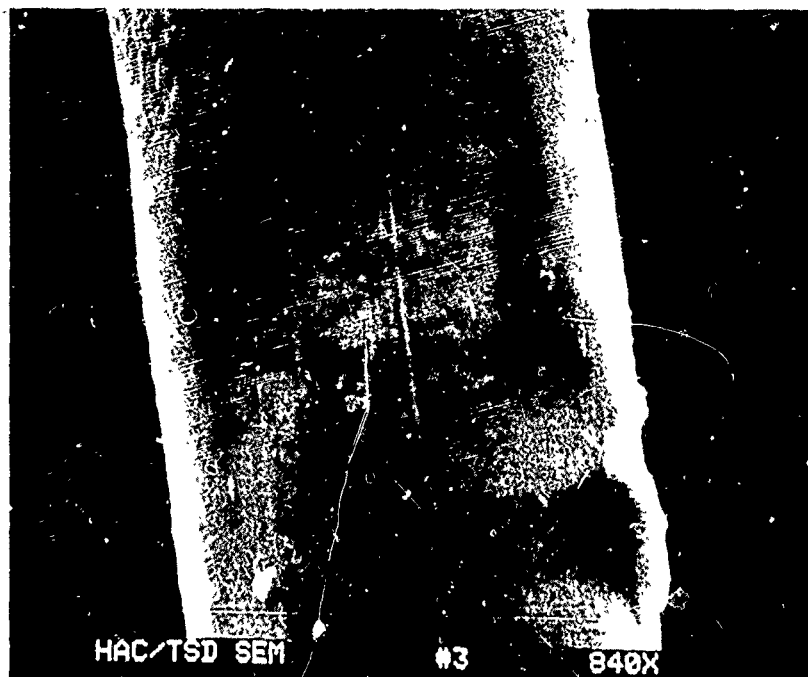


Figure 8-9. Effect of laser exposure on JW 1177/12 type H2 wire, AWG 40.

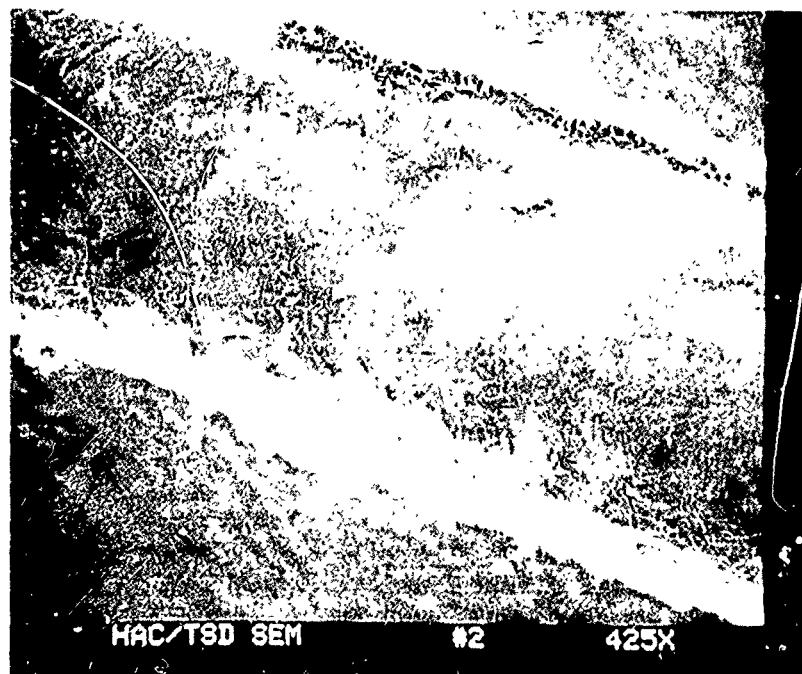


Figure 8-10. Effect of laser exposure on JW 1177/15, type M wire, AWG 36.

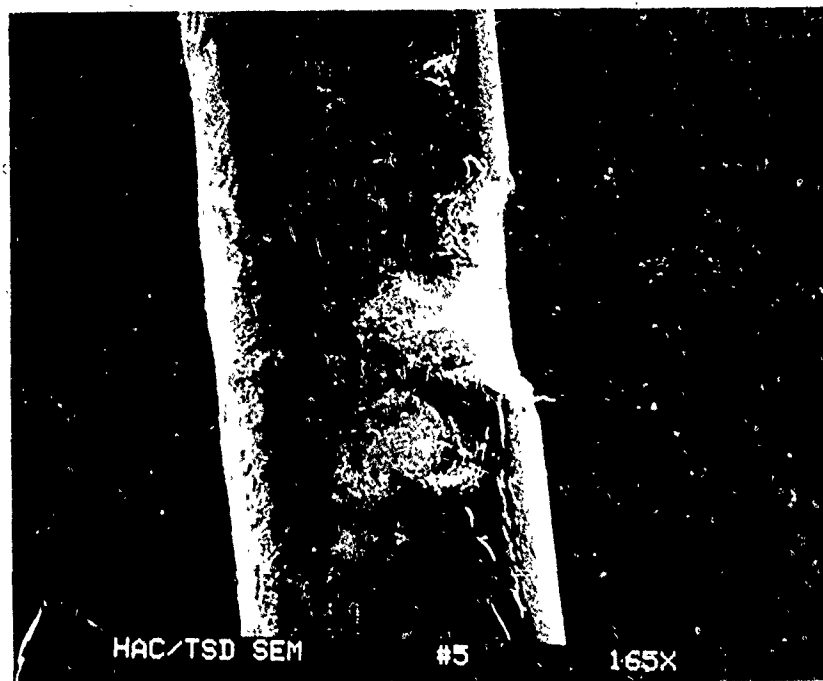


Figure 8-11. Effect of laser exposure on JW 1177/14, type K2 wire, AWG30.

8.2 MAGNET WIRE JOINING TECHNIQUES

The fragility of the magnet wire leads from magnetic coils wound with fine and ultrafine magnet wire, then encapsulated, requires precautions to be taken to increase the breaking strength of such leads. Usually this is done by joining the fine wire to a heavier wire capable of withstanding the handling and thermal stresses caused by the encapsulant. The joint between the two wires, normally widely different in diameter, must have mechanical strength adequate to allow it to be buried during subsequent winding and taping operations. Another normal requirement is that the joint must also have low electrical resistance. This resistance must remain essentially constant over the operating life of the component.

Various joining processes were investigated and the results evaluated and compared to determine their practicality and improvement on reliability. The joining techniques evaluated were:

1. Laser welding
2. Conductive adhesive bonding
3. Soldering
4. Crimping
5. Parallel gap welding
6. Ultrasonic bonding
7. Thermosonic bonding
8. Skeining

Techniques evaluated involved joining fine and ultrafine magnet wire guages ranging from AWG 52 to AWG 42, to AWG 36 solid copper wire. Techniques 5 to 7 investigated the joining of AWG 40 copper magnet wire only to AWG 36 solid copper lead wire, both sizes with and without nickel coatings. With the exception of the wire used in the skeining reinforcement process, all magnet wires in this investigation were Type M per JW 1177/15. Removal of this insulation was accomplished by chemical stripping in accordance with HPR 40004 using HMS 20-1699 Type II (Lonco PT-5-ML) stripper.

Insulation on the wire used for skeining was of Type U per JW 1172/2 and was removed thermally during the solder tinning operation.

Test methods used to evaluate and compare the interconnection techniques were:

- a. Interconnection resistance, measured to four significant figures, using a low resistance Kelvin bridge
- b. Joint pull strength, with a Chatillion tester, pull rate 0.7 in/min
- c. Visual examination, 20 x microscope
- d. Metallographic examination, using standard techniques.

8.2.1 Laser Welding

Two manufacturers of laser welding equipment were contacted regarding the feasibility of joining fine magnet wire to the intermediate lead AWG 36. Both manufacturers, COHERENT RADIATION, Inc. and COMPULASER, Inc., (Ref 16.2.d) agreed to prepare sample welds for evaluation, but later, COMPULASER did not because of equipment problems.

Samples of AWG 44 and 48 magnet wires attached to AWG 36 lead wires were joined by COHERENT using a 50 watt neodymium glass laser and returned to Hughes for evaluation. They reported difficulty in making welded connections, stating that a fixture would be required to make the 10 samples requested by HAC for test purposes. Only two tests, visual and metallographic examination, was performed on one weld. SEM photographs of the laser welded wires are shown in Figures 8-12 and 8-13, which shows a spherical formation. A microsection of the weld is shown in Figure 8-14, indicating that a true weld was made as indicated by the fusion of the two wires.

Simultaneously, welds were attempted with a small, 4-watt YAG laser at Hughes, using similar wire configurations, without success.



Figure 8-12. AWG 48 magnet wire laser welded to AWG 36 magnet wire, 86X.

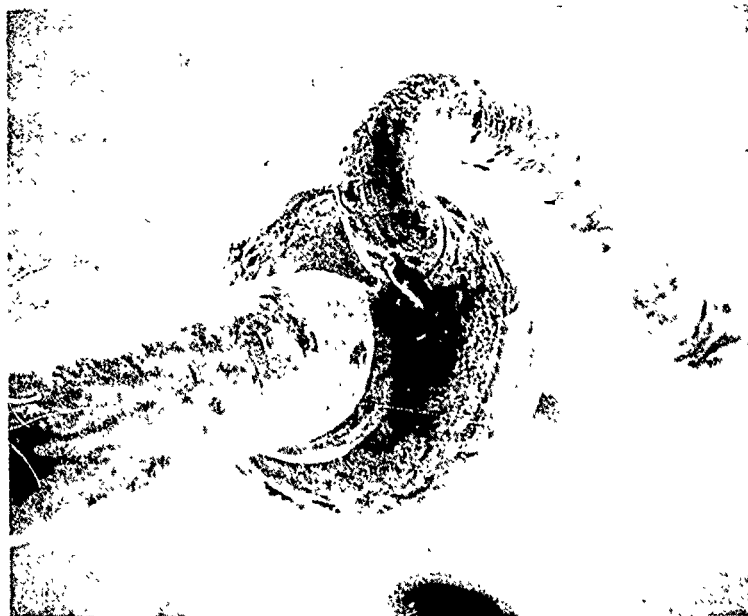


Figure 8-13. AWG 48 magnet wire laser welded to AWG 36, 180X.



Figure 8 14. Microsection of laser weld showing complete fusion of wire.

8.2.2 Conductive Adhesive Bonding

Samples of AWG 44 and AWG 52 magnet wires were stripped and attached to AWG 36 solid copper wires by wrapping the smaller wire around the larger four to six turns. Conductive adhesive (Eccobond 56C per HMS 20-76 Type 2 Class 2) was applied by dipping the wires in the adhesive to cover the wrapped area. A spatula was used to spread the adhesive evenly and to remove sharp projections. The samples were cured at room temperature for 8 hours, then baked in an oven at 165°F for 48 hours to simulate aging. Because of the very viscous nature of the highly silver-filled adhesive, the handling required in applying the adhesive proved to be very difficult and several samples of the AWG 52 wire broke during sample preparation.

The joining area where the conductive adhesive was applied appeared very rigid. Any flexing of the wire at the joint area resulted in cracking and peeling of the conductive adhesive. An example of an adhesive bonded wire connection is shown in Figure 8-15.

The results of the joint resistance tests for size AWG 44 wire specimens are shown in Table 8-1. Wire breakage due to damage by the instrument contacts prevented measurement of joint resistance of connections made with AWG 52 wire.

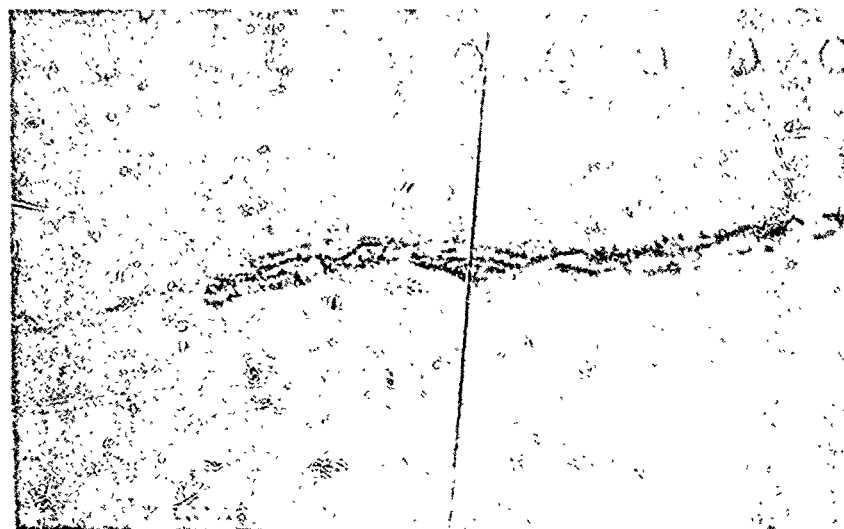


Figure 8-15. Wire connection bonded with conductive adhesive.

TABLE 8-1. JOINT RESISTANCE (AWG 44 to AWG 36 MAGNET WIRE)

Attachment Process	Material	Number of Samples	Joint Resistance (ohms)		
			Min	Max	Avg
Solder Alloy	50% Indium, 50% Lead	10	0.022	0.053	0.040
	25% Indium, 75% Lead	7	0.015	0.064	0.041
	20% Tin, 80% Lead	9	0.030	0.065	0.046
	10% Tin, 88% Lead, 2% Silver	7	0.010	0.080	0.068
Conductive Adhesive	Eccobond 56C	9	0.056	0.099	0.080
Crimping	Lead Foil	8	0.089	0.50	0.21
Laser Welding	Magnet Wire	1	Not Tested		

Difficulty in application resulted in a rough, irregular appearing connection. The joint resistance appeared slightly higher than the solder joint resistance. The strengths of the connections made with conductive adhesive are equal to those made with solder. Joint strengths are presented in Tables 8-2 and 8-3. Wire breakage during joint strength pull testing occurred in 100 percent of the specimens tested.

It is concluded that conductive adhesive bonding is not a viable process for connecting fine magnet wires because of difficulty in application and the tendency of the adhesives to peel away from the connection during handling.

8.2.3 Soldering

The conventional process for joining fine and ultrafine wires to copper intermediate lead wires in magnetic assemblies is with solder alloys containing high percentage of tin. The problem with high tin solders is that the tin readily dissolves fine copper wire at soldering temperatures, causing

TABLE 8-2. JOINT STRENGTHS (AWG 44 TO AWG 36 MAGNET WIRE)

Attachment Process	Material	Number of Samples	Joint Strength (Oz)		
			Min	Max	Avg
Solder Alloy	50% Indium, 50% Lead	6	47.5	47.8	47.6
	25% Indium, 75% Lead	7	47.3	48.6	47.8
	20% Tin, 80% Lead	8	47.0	47.7	47.3
	10% Tin, 88% Lead 2% Silver	7	41.3	49.4	47.0
Conductive Adhesive	Eccobond 56C	10	40.0	45.8	44.5
Crimping	Lead Foil	10	38.4	46.4	43.7
Laser Welding	Magnet Wires	1	Not Tested		
Tensile Strength	AWG 44 Wire	5	55.0	58.3	56.3

TABLE 8-3. JOINT STRENGTHS (AWG 52 TO AWG 36 WIRE)

Attachment Process	Material	Number of Samples	Joint Strength (Oz)		
			Min	Max	Avg
Solder Alloy	50% Indium, 50% Lead	8	8.7	9.7	9.0
	25% Indium, 75% Lead	7	8.5	9.3	9.1
	20% Tin, 80% Lead	8	8.4	9.5	9.2
	10% Tin, 88% Lead, 2% Silver	6	8.5	9.0	8.8
Conductive Adhesive	Eccobond 56C	-	-	-	-
Crimping	Lead Foil	10	9.1	10.5	9.5
Tensile Strength	AWG 52 Wire	3	10.7	10.7	10.7

rapid deterioration of the wire strength; even complete dissolution of the copper wire can occur in relatively short times leaving no wire interconnection. This problem of dissolution of fine wire was attacked in two directions. First, and most obvious, is the evaluation of low tin or tin-free solders, and second, careful control of the soldering parameters such as temperature, soldering iron size, and duration of application with conventional tin-lead solders.

Solder connection test samples were made using the four different types of solder in Table 8-4. These solder alloys were recommended by the solder manufacturers for soldering fine copper wires and were also chosen because of their wetting and low copper solubility characteristics. Solder iron tip temperatures used and relative ease of use (because of the wetting characteristics) of each solder alloy is also presented in Table 8-4.

Samples of AWG 36 and AWG 44 magnet wires were tinned prior to wrapping and soldering. Tinning of the AWG 52 was awkward and could not be accomplished because the wire was not "stiff" enough to allow it to be submerged in the denser solder. Alloys used for tinning were the same as those used to solder the connections.

All solder joints were made with the smaller size wires wrapped four to six turns around the larger AWG 36 wire.

TABLE 8-4. SOLDER ALLOYS USED FOR INTERCONNECTIONS

Solder Alloy	Temperature °F		Solder Iron Tip Temp °F	Wettability (Ease of Soldering)
	Liquidus	Solidus		
50% Indium 50% Lead	408	356	600	Best
25% Indium 75% Lead	508	440	700	Good
20% Tin 80% Lead	536	361	700	Poorest
10% Tin 88% Lead 2% Silver	570	514	800	Good

Tinning and soldering was accomplished using MIL-F-14256, Type RMA flux (Alpha 611).

A photograph of an example of fine magnet wire soldered to a larger lead wire is shown in Figure 8-16.

Typical metallographic cross sections of the solder joints made with AWG 44 and AWG 52 wire jointed to AWG 36 lead wire are shown in Figures 8-17 and 8-18. A photograph of soldered connections showing copper-tin intermetallic alloy layer with indium-lead and tin-lead solders can be seen in Figures 8-19 and 8-20, respectively.

The resistance of soldered connections made with AWG 44 wire tabulated in Table 8-1, shows that there is virtually no difference as a result of the four solder alloys used. Measurement of joining resistance could not be performed on connections made with AWG 52 because the ultra-fine wire was too fragile to withstand the force of the measuring instrument contacts.

Solder joint strengths were presented in Tables 8-2 and 8-3. It should be pointed out that the strengths of the soldered connections exceeded the strength of the smaller size wire and the mode of pull test failure was wire breakage and not solder failure.

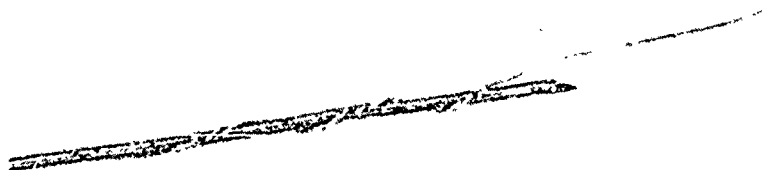


Figure 8-16. Solder connection showing AWG 52 wrapped over AWG 36 wire, 145X.

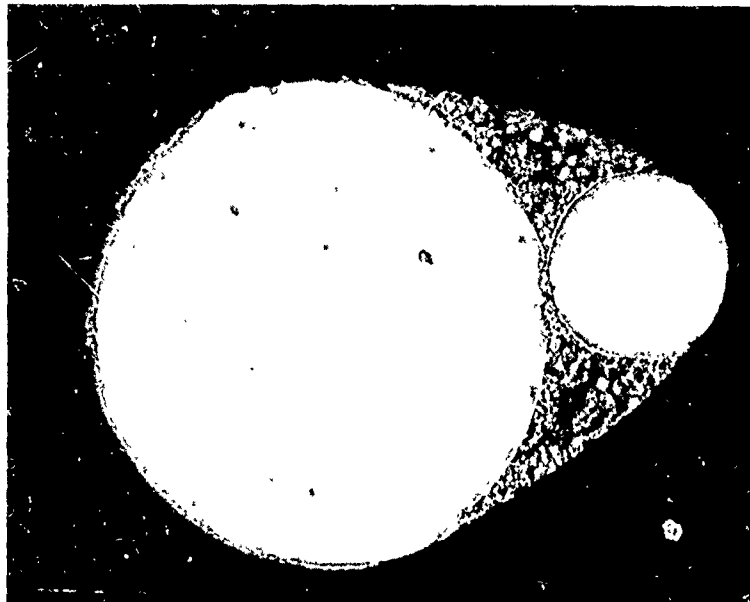


Figure 8-17. Microsection of soldered AWG 44 wire to AWG 36 wire, 500X.

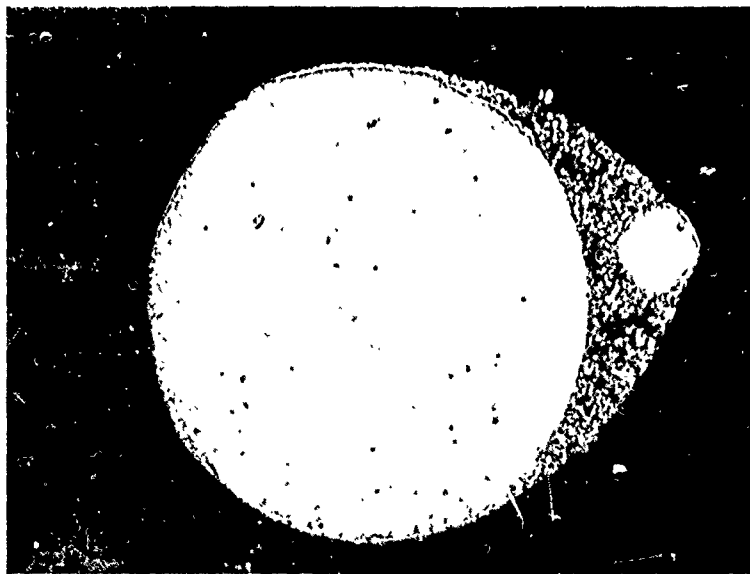


Figure 8-18. Microsection of soldered AWG 52 wire to AWG 36 wire, 500X.



Figure 8-19. Intermetallic layers formed on copper wires soldered with 50% indium, 50% lead solder alloy, 2000X.



Figure 8-20. Intermetallic layers formed on copper wires soldered with 20% tin, 80% lead, 2000X.

Metallographic examination of the connections made with the various alloys showed that dissolution of the wire in the solder was only slight with the greatest reduction in wire size being approximately 0.0002 inch or 10 percent. A copper/tin intermetallic alloy layer was observed on all samples. The thickness of the copper/tin intermetallic layers ranges from 0.000028 to 0.000035 inch.

It is concluded that any of the four solder alloys can be used to make connections with fine copper wires without fear that the fine wire will dissolve in the solder if normal manufacturing soldering times and temperatures are closely observed.

8.2.4 Crimping

The AWG 44 and AWG 52 wires were stripped of insulation and then wrapped four to five turns around the AWG 36 wires. The wrapped wires were then inserted between folded 0.008 inch thick lead foil and crimped using long nose pliers. The crimping pressure was calculated to be approximately 5000 psi.

Figure 8-21 shows a connection made with the folded piece of lead foil. A microsection of the connection can be seen in Figure 8-22.

The electrical resistance of joints made by crimping the small fine wires and larger lead wire in lead foil was much greater than those made using the soldering or adhesive bonding processes. The minimum, maximum and average values were presented in Table 8-1.

Two of the ten AWG 44 wire crimped connections tested for pull strength pulled apart (wire pulled out of the connection). All other connections, including those made with AWG 52-wire, failed when the small wire broke near the crimped area. Test results are presented in Tables 8-2 and 8-3.



Figure 8-21. Lead foil crimped connection, AWG 52 and 36 wires, 15X.

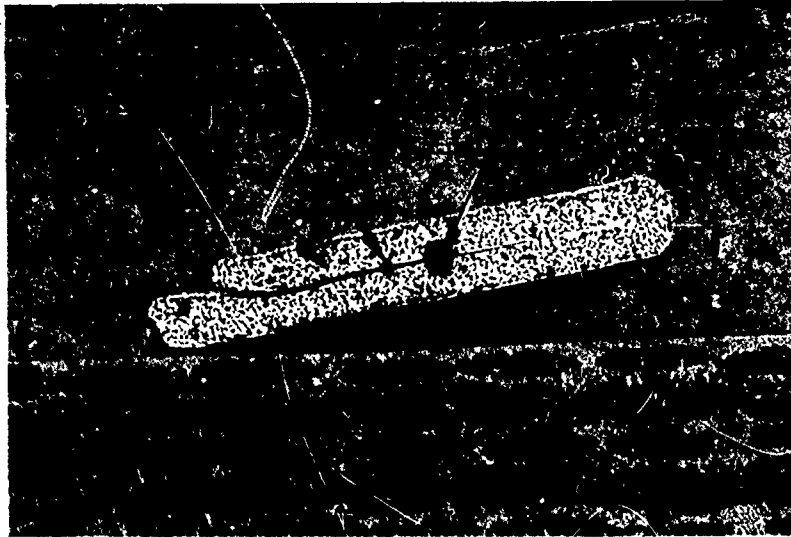


Figure 8-22. Microsection of lead foil crimped connection, showing indentation of the wire in the lead foil.

Metallographic examination of crimped connections indicated that the pressure used to make the connection was not enough to embed the smaller wires entirely in the lead foil leaving gaps between the lead and the wire.

It was also noted that joint integrity could not be determined by visual examination.

It is concluded that mechanical connections such as those evaluated here, are not acceptable for fine wire attachment because of the poor mechanical retention and because of the difficulty of determining acceptability by visual examination.

8.2.5 Parallel Gap Welding

Parallel gap welding was done using each combination of wires. The wires were actually bonded together, but there was no pull strength to be noted. The bond pulled apart at the foot. Results could possibly be improved with the design of a fixture to hold the wires in place while the welding is done; however, in view of the better results obtained in the previously reported interconnection methods, further work was not warranted.

8.2.6 Ultrasonic Bonding

Ultrasonic bonding could not be achieved with the equipment and technology available; consequently, no further work was done.

8.2.7 Thermosonic Bonding

The thermosonic bonder, at a maximum of 150°C, did not operate at a sufficiently high temperature to cause any bonding of the wires. Investigation showed that thermosonic bonders are restricted by their inherent characteristics such as, operating on too low a temperature range and the high thermal resistivity of copper, to adequately bond AWG 40 copper magnet wire to AWG 36 intermediate leads, so no further work was done.

8.2.8 Skeining

A method of achieving reinforcement of fine wire coil leads which does not require the use of an intermediate solid wire such as the AWG 36 wire, and can be done with automatic equipment before and after the winding operation, is "skeining". Without cutting the fine wire, it is looped back and forth, followed by a close wrap of the bundle. In automatic winding machinery, the fine wire is not cut, continuing on as the "start" to the next coil. The coils are then separated by cutting the skeins in the middle.

After soldering both ends which effectively parallels all wires in the bundle, the one end is anchored in the winding by suitable taping or other means, and the other end soldered to a terminal, or stranded lead wire to the outside world. Samples of AWG 42 automatically skeined wires with a Type U polyurethane coated insulation, which is heat strippable in molten solder, were obtained from the skeining equipment manufacturer.

An example of a skeined wire before and after tinning can be seen in Figure 8-23. A longitudinal cross-section of a soldered skeined wire is shown in Figure 8-24. Metallographic examination of the skeined wire showed that the Type U polyurethane insulation was completely removed from the wire by the solder tinning operation.

Resistance measurements made on skeined wires are presented in Table 8-5. Since skeining involves only a single wire (no second attached

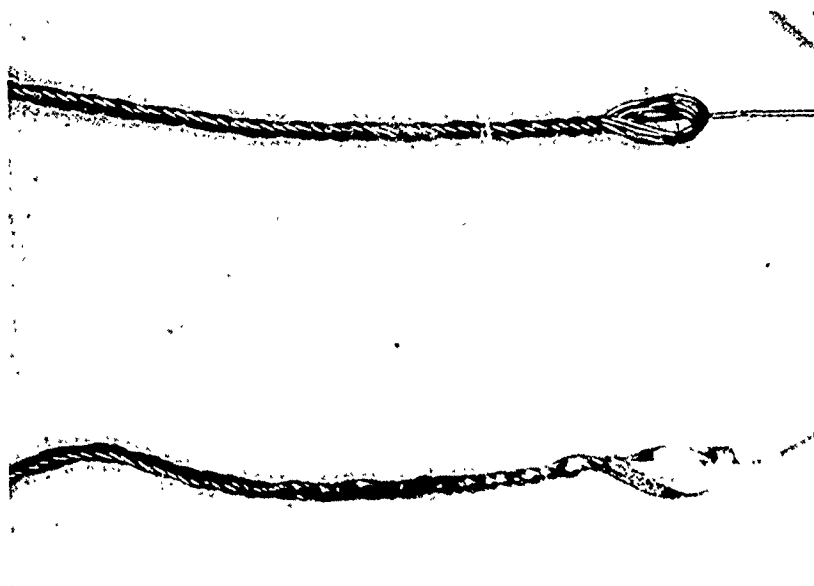


Figure 8-23. Skewed wire before and after tinning, 10X.

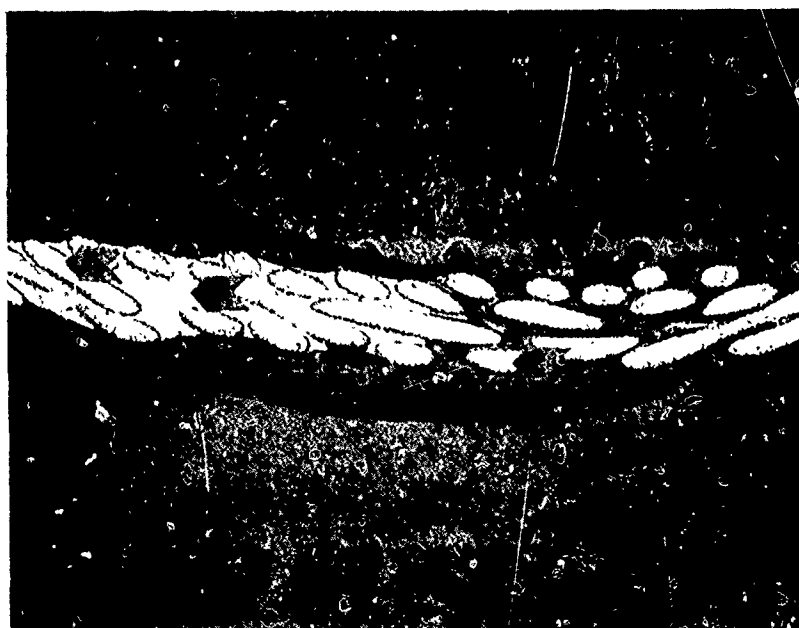


Figure 8-24. Longitudinal cross section of tinned and untinned portion of skewed AWG 48 wire: A = copper wire, B = Solder, C = untinned wires, 30X.

TABLE 8-5. RESISTANCE OF SKEINED WIRES
BEFORE AND AFTER TINNING

Before Tinning (ohms)	After Tinning (ohms)
12.35	0.1750
12.05	0.1710
11.80	0.1877
11.98	0.1636
12.20	0.1735

wire), no comparison can be made with the "two-wire" connection. The only conclusion that can be reached is that the tinning operation was effective in removing the wire insulation and produced skeined wire bundles with consistent resistance values.

Specific applications of this method of fine wire termination in high reliability components are not known at this time. Application may be very limited due to the inherent requirement that the fine wire have a solder strippable insulation, while in contrast high reliability components nearly always require high temperature insulation, which is not solder strippable. Removal of this insulation from the end of a fine wire bundle or skein by other methods than solder stripping, which must be complete to ensure that all wires in the bundle are paralleled to minimize the resistance, does not seem promising at the present time.

8.3 SIZE REQUIREMENTS FOR INTERMEDIATE LEADS

Transformer windings using fine and ultrafine wire sizes have an additional design and packaging consideration, that of interfacing the windings with the outside world. The problem occurs because of the large difference in thermal expansion coefficients between copper and the available encapsulation compounds which stresses the interface wires during thermal cycling. Because of this the fragility of fine wire precludes its passing through the encapsulation material in a straight line for any distance.

The conventional method employed to overcome this problem is the termination of the fine wire onto an intermediate lead wire of larger diameter capable of withstanding the thermal stresses of the encapsulation. The joint with the intermediate wire is usually taped into the winding so that during the encapsulation process it becomes part of the winding assembly. Another method employed, but not used as often, is skeining (Paragraph 8.2.8), where the fine wire is looped back and forth several times and then close wrapped spirally around the bundle. After soldering both ends to join all the strands together, the one end is taped into the winding and the other connected to the terminal through the encapsulation.

The gauge of the intermediate lead is allowed to be as small as AWG 36 at a NASA facility, while at Hughes the minimal allowable size is AWG 30. No particular rationale could be found for these selections, other than being stated that it was just "good practice". The following section analyzes the stresses on a straight wire coaxially enclosed in an encapsulant cylinder.

8.3.1 Intermediate Lead Size Analysis

Based on the steel bolt and bronze sleeve problem in Timoshenko and MacCullough (Reference 14.1) a model of a straight wire enclosed by a cylindrical, coaxial encapsulation compound, as shown in Figure 8-25. This analysis is based on the following assumptions:

- a. Compressive force on the cylindrical ends of the encapsulant equals the total tension in the wire. In other words, this assumes that wire is attached to rigid end plates which transmit the tensile forces completely from encapsulant to the wire. No localized deformation around the immediate vicinity of the wire of the encapsulant is assumed.
- b. Extension of the wire, due to temperature rise plus stretch of the wire due to the total force exerted on the wire, equals extension of encapsulant due to rise of temperature, minus the compression of the encapsulant due to the total force exerted by the wire.

Expressed in equation form, the above is

$$\epsilon_w \ell (t_2 - t_1) + \frac{\rho_w \ell}{A_w E_w} = \epsilon_e \ell (t_2 - t_1) - \frac{\rho_e \ell}{A_e E_e} \quad (1)$$

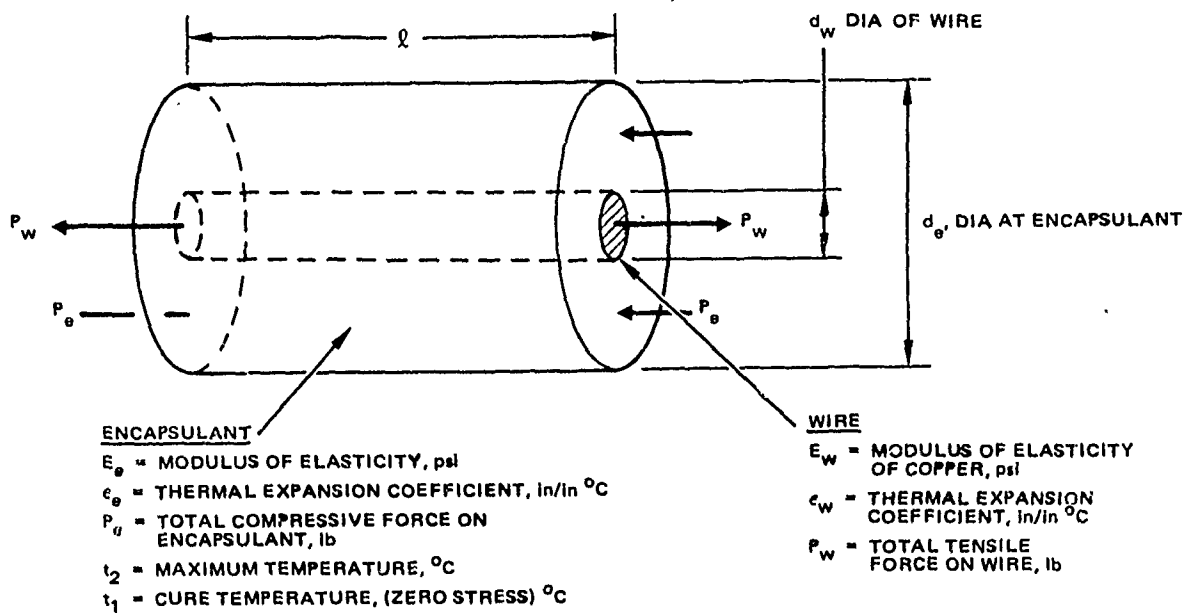


Figure 8-25. Wire-encapsulant stress model.

where:

- ϵ_w = average thermal expansion coefficient of copper wire
- ϵ_e = average thermal expansion coefficient of encapsulation
- l = length
- t_2 = upper temperature limit in $^{\circ}\text{C}$
- t_1 = lower temperature limit in $^{\circ}\text{C}$
- P_w = total force in wire
- A_w = cross sectional area of wire, in²
- E_w = modulus of elasticity of copper
- P_e = total force on ends of encapsulant
- A_e = cross sectional area of encapsulation, in²
- E_e = modulus of elasticity at encapsulant, psi

By Statement (a), $\rho_w = \rho_e$, and lengths l cancel,

Solving for ρ_w , the force on the wire,

$$\rho_w = \frac{(\epsilon_e - \epsilon_w)(t_2 - t_1)}{(1/A_w E_w) + (1/A_e E_e)} \quad (2)$$

Letting d_e , d_w be the diameters of the wire and encapsulant, respectively,

Case I

$d_e = \text{constant}$; i. e., diameter of encapsulant cylinder is constant regardless of wire diameter.

The effective cross sectional area of encapsulant A_e is

$$A_e = \frac{\pi d_e^2}{4} - A_w = \frac{\pi}{4} (d_e^2 - d_w^2) \quad (3)$$

Then

$$\rho_w = \frac{\pi}{4} \frac{(\epsilon_e - \epsilon_w)(t_2 - t_1)}{(1/d_w^2 E_w) + [1/(d_e^2 - d_w^2) E_e]} \quad (4)$$

Wire stress, $S_w = \rho_w / A_w = 4\rho_w / \pi d_w^2$

Case II

$(d_e - d_w) = c = \text{constant}$; i. e., thickness of encapsulant is constant over wire diameter

$$\rho_w = \frac{\pi}{4} \frac{(\epsilon_e - \epsilon_w)(t_2 - t_1)}{(1/d_w^2 E_w) + [1/(c^2 + 2cd_w) E_e]} \quad (5)$$

Quantities for the cure temperature and wire diameter are used as parameters.

Corresponding to the Case I and Case II assumptions, two computer programs were developed for the HP-67/97 hand-held programmable calculators and are listed in Appendix 16.1. As mentioned in the derivation, Case I assumes that the diameter of the coaxial cylinder of plastic coaxially enclosing the wire remains constant. As the diameter (cross sectional area) of the wire increases the corresponding quantity of the encapsulation material decreases. Case II resulted from the consideration that, at least for high voltage applications where the thickness of insulation is required to be constant, the thickness of insulation over the wire, or the difference between the wire and encapsulation diameters, remains constant. The various constants, which are used in the equation as parameters, are given below in the order of entry into the storage registers of the calculators. The rationale for the selection of the values is also noted where applicable.

- Register 1: t_2 , 100°C, high temperature limit. This temperature represents the highest that the encapsulated component will be exposed to during acceptance testing, or actual operation.
- Register 2: t_1 , originally selected at -40°C, the lower limit of temperature cycling during testing, it was realized that this temperature should be the curing temperature of the encapsulation material. This conclusion is based on the realization that during the cure cycle the internal stresses are essentially zero. At temperatures lower than the cure temperature, because of the greater expansion coefficient of the encapsulation compound, the stress on the wire will be compressive which would not cause the wire to fracture. The initial cure temperatures used in the analysis for the three encapsulation systems were listed as follows:

Epon 825/HV:	74°C (165°F)
Scotchcast 255:	93°C (200°F)
Uralane 5753:	93°C (200°F)

For a comparison, the analysis also includes the regular range of temperature, from -40°C to +100°C.

- Register 3: ϵ_w , thermal expansion coefficient of copper,
 16×10^{-6} in/in°C

Register 4: ϵ_e , thermal expansion coefficient for the encapsulant varies with temperature itself, but is assumed constant to facilitate this analysis. Referring to the tables and data in Volume I, the average values for this coefficient, and the temperature range over which it is taken, are as follows:

Scotchcast 255:

172×10^{-6} in/in $^{\circ}$ C (55 to 70 $^{\circ}$ C)

Refer to Table 3-4, Volume I, page 3-14

Epon 825/HV:

65×10^{-6} in/in $^{\circ}$ C (+25 to +125 $^{\circ}$ C)

Refer to Volume I, page 3-15

Uralane 5753:

250×10^{-6} in/in $^{\circ}$ C (temperature range not stated)

Refer to Table 3-2, Volume I, page 3-11

In the case of Scotchcast 255, for lack of better data, the TCE is assumed the same to 100 $^{\circ}$ C.

Register 5: Modulus of Elasticity (Young's modulus) for copper, 17×10^6 psi.

Register 6: Modulus of elasticity for structural plastic materials were not readily available; values for encapsulation materials were difficult to obtain and some question exists as to their validity. Values used in this analysis:

Scotchcast 255: 10^5 psi

Epon 825/HV: 5×10^5 psi

Uralane 5753: 10^3 psi

Register 7: Case I, diameter of encapsulant, 0.3 inch; Case II, constant thickness of encapsulant above wire, 0.15 inch.

8.3.1.1 Results of Analysis

Using the above constants as parameters in the computer programs, calculations of the stresses in various sizes of wires ranging from AWG 63, 0.00022 inch diameter to AWG 1, (0.289 inch diameter) were made and listed in Table 8-6. Where the smaller wire sizes have a cross-sectional area small in comparison with the total cross-section area of the encapsulant, the stress on the wire is a constant. When the cross-sectional areas of the wire become significant with respect to those of the encapsulant, then stresses rapidly decrease.

TABLE 8-6. TABULATION OF WIRE STRESS CALCULATIONS

		EPON 825/HV						SCOTCHCAST 255						Uralane 5753																			
		Case I			Case II			Case I			Case II			Case I			Case II																
AWG	Dia. In.	t _i = 74°C		P _w	t _i = -40°C		P _w	t _i = 74°C		P _w	t _i = -40°C		P _w	t _i = 93°C		P _w	t _i = -40°C		P _w	t _i = 93°C		P _w	t _i = -40°C		P _w	t _i = 93°C		P _w	t _i = -40°C		P _w		
		S _w	P _w		S _w	P _w		S _w	P _w		S _w	P _w		S _w	P _w		S _w	P _w		S _w	P _w		S _w	P _w		S _w	P _w		S _w	P _w		S _w	P _w
63	0.00022	0.00082	21.6	0.0044	116.6	0.001	21.7	0.004	116.6	0.00077	18.6	0.014	371.2	0.001	18.6	0.014	371.2	0.001	27.6	0.021	552	0.001	27.6	0.021	552	0.001	27.6	0.021	552	0.001	27.6	0.021	552
57	0.00044	0.0033	21.6	0.018	116.6	0.003	21.7	0.018	116.6	0.0028	18.6	0.056	371.1	0.003	18.6	0.056	371.1	0.004	26.8	0.082	537	0.004	26.9	0.082	537	0.004	26.9	0.082	537	0.004	26.9	0.082	537
52	0.00078	0.010	21.6	0.056	116.6	0.010	21.6	0.056	116.6	0.009	18.5	0.177	370.9	0.009	18.5	0.177	370.9	0.012	24.9	0.24	499	0.012	25.0	0.24	499	0.012	25.0	0.24	499	0.012	25.0	0.24	499
50	0.00095	0.015	21.6	0.083	116.6	0.015	21.6	0.083	116.6	0.013	18.5	0.263	370.6	0.013	18.5	0.263	370.7	0.017	23.8	0.34	475	0.017	23.8	0.34	475	0.017	23.8	0.34	475	0.017	23.8	0.34	475
44	0.002	0.068	21.6	0.366	116.4	0.068	21.6	0.366	116.4	0.058	18.4	1.15	363.5	0.058	18.4	1.16	368.5	0.045	15.9	1.0	319	0.050	15.9	1.0	319	0.050	15.9	1.0	319	0.050	15.9	1.0	319
36	0.005	0.42	21.4	2.27	115.5	0.42	21.5	2.27	115.6	0.348	17.7	6.96	354.5	0.349	17.7	6.97	355.0	0.096	4.9	1.91	97.3	0.098	5.0	1.96	100	0.098	5.0	1.96	100	0.098	5.0	1.96	100
30	0.010	1.64	20.9	8.8	112.4	1.64	20.9	8.85	112.6	1.23	15.6	24.5	312.2	1.24	15.8	24.8	315.4	0.11	1.4	2.20	38.0	0.117	1.5	2.34	29.8	0.117	1.5	2.34	29.8	0.117	1.5	2.34	29.8
27	0.0142	3.19	20.1	17.2	108.3	3.21	20.2	17.3	109.0	2.13	13.4	42.6	268.7	2.18	13.8	43.6	275.4	0.11	0.71	2.25	14.2	0.123	0.78	2.46	15.6	0.123	0.78	2.46	15.6	0.123	0.78	2.46	15.6
25	0.0179	4.86	19.3	26.2	104.0	4.92	19.5	26.5	105.2	2.91	11.5	58.1	231.0	3.03	12.0	60.6	241.0	0.11	0.45	2.27	9.0	0.127	0.50	2.54	10.1	0.127	0.50	2.54	10.1	0.127	0.50	2.54	10.1
22	0.0253	8.76	17.4	47.1	93.8	9.02	17.9	48.6	96.6	4.2	8.4	84.2	167.4	4.59	9.1	91.7	182.5	0.11	0.23	2.28	4.5	0.134	0.27	2.68	5.3	0.134	0.27	2.68	5.3	0.134	0.27	2.68	5.3
20	0.0320	12.5	15.6	67.4	83.8	13.2	16.4	71.1	88.4	5.05	6.3	101.0	125.6	5.75	7.1	115	143.1	0.11	0.14	2.28	2.8	0.140	0.17	2.79	3.5	0.140	0.17	2.79	3.5	0.140	0.17	2.79	3.5
18	0.0403	17.0	13.3	91.6	71.8	18.6	14.6	100	78.0	5.7	4.5	114.8	90.0	6.93	5.4	138	108.6	0.11	0.088	2.27	1.8	0.146	0.11	2.43	2.3	0.146	0.11	2.43	2.3	0.146	0.11	2.43	2.3
16	0.0508	21.9	10.8	118	58.2	25.4	12.5	136	67.5	6.3	3.1	125.0	61.7	8.11	4.0	162	80.0	0.11	0.055	2.24	1.1	0.155	0.076	3.09	1.5	0.155	0.076	3.09	1.5	0.155	0.076	3.09	1.5
10	0.1019	32.5	4.0	175	21.4	52.9	6.5	285	35.0	6.5	0.80	130.7	16.0	11.9	1.5	238	29.3	0.10	0.012	2.04	0.25	0.194	0.024	3.85	0.48	0.194	0.024	3.85	0.48	0.194	0.024	3.85	0.48
7	0.144	31.6	1.9	170	10.4	70.6	4.3	380	23.3	5.8	0.36	116.5	7.1	14.4	0.88	288	17.7	0.089	0.005	1.78	0.11	0.227	0.014	4.54	0.28	0.227	0.014	4.54	0.28	0.227	0.014	4.54	0.28
4	0.204	23.4	0.72	126	3.8	92.4	2.8	497	15.2	4.1	0.13	82.4	2.5	17.7	0.54	254	10.8	0.062	0.002	1.24	0.038	0.273	0.008	5.46	0.17	0.273	0.008	5.46	0.17	0.273	0.008	5.46	0.17
1	0.289	3.23	0.05	17.4	0.26	120.6	1.8	649	9.9	0.56	0.008	11.1	0.17	22.2	0.34	443	6.7	0.008	0.0001	0.167	0.002	0.339	0.005	6.78	0.10	0.339	0.005	6.78	0.10	0.339	0.005	6.78	0.10

Notes: Case I Constant diameter of encapsulant, dc = 0.3 in.
Case II Constant thickness of insulation

$\frac{d_c - d_w}{2} = C = 0.15$ in.

P_w = wire tensile force 20 in. lb.
S_w = wire stress = $\frac{P_w}{A_w}$ = kilo psi

Left hand t_i temperature = cure temperature of encapsulant, °C
Right hand t_i temperature = -40°C.
Underlined values close to elastic limit of copper = 17,000 psi. AWG sizes smaller subject to permanent deformation.

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Underlined values close to elastic limit of copper = 17,000 psi. AWG sizes smaller subject to permanent deformation.

This is true for both programs except that for Case I, with the fixed diameter of encapsulation, the decrease in stress rolls off faster than in Case II.

Assuming that the copper yield stress is approximately 17,000 psi the sizes of wire which would not be damaged by the thermal expansion of the insulation is summarized for Case I and II for the three encapsulation systems in Table 8-7.

The specification requirements for intermediate leads allowed by various organizations for high reliability components runs from AWG 36 to about AWG 30. A selection of too large a diameter of intermediate lead, in comparison with the fine and ultrafine wire, increases probability of breaking during the soldering and tapin operation. Consequently, it is recommended that AWG size 30 be used as a general rule. For specific applications, other temperature ranges, or different parameter of other encapsulents, the computer program can be used to analyze the most desirable and safe size.

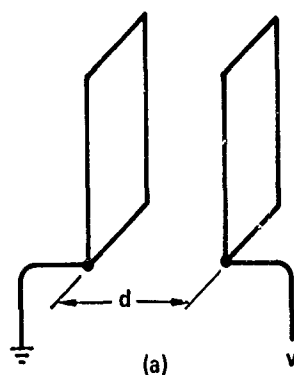
8.4 RADII OF CONNECTIONS AS A FUNCTION OF OPERATING VOLTAGE

It is common knowledge that improvement of reliability in high voltage components can be achieved by decreasing the voltage gradient existing between high and low voltage conductors. Methods of determining the maximum gradient points in high voltage components and estimating their magnitudes is a necessary requirement for the design. Exact calculation of voltage gradients for even the simplest of geometries, usually involves a completed equation. Considering the accuracies of the data available, approximate equations are sufficient to be of the orders of magnitude expected for the maximum gradients. Units used to express voltage gradients are volts-per-mil (thousandths of an inch) or kilovolts-per-millimeter (centimeter).

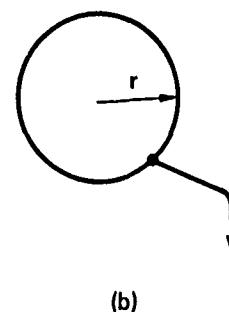
Two simple configurations, which give an easy method estimating voltage gradients as a first approximation are the parallel plates and isolated sphere as shown in Figure 8-26. As can be seen, the voltage gradient between parallel plates is equal to the applied voltage divided by the distance. If this is in mils, then the voltage gradient is volts-per-mil which is a constant between parallel plates. In Figure 8-26b, the case of an isolated sphere with the return at infinity, the voltage gradient is a maximum at the surface of the sphere and equal to the applied voltage divided by the radius

TABLE 8-7. SUMMARY OF ENCAPSULATED WIRE STRESS LIMITS

Material	Lower Temperature Limit, °C	Case	Wire AWG for 1.7 kpsi approx.
Epon 825/HV	74	I	22
	74	II	21
	-40	I	9
	-40	II	4
Scotchcast 255	93	I	34
	93	II	30
	-40	I	10
	-40	II	7
Uralane 5753	93	I	45
	-40	I	28
	-40	II	27



PARALLEL PLATES, SEPARATION d
UNIFORM VOLTAGE GRADIENT $= \frac{V}{d}$



ISOLATED SPHERE, RADIUS r
MAXIMUM VOLTAGE GRADIENT
ON SURFACE $= \frac{V}{r}$








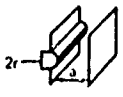
Figure 8-26. Simplified voltage gradient calculations.

of the sphere in mils. If the ground plane is 5 radii from the sphere then the voltage gradient calculated, using the isolated sphere equation, is 20% low. Both these equations give a simple, quick and easy estimation of voltage gradients and can be used as a first approximation in the layout and design of high voltage conductors and insulation requirements.

Other geometries which are nearly always present in high voltage magnetic devices are represented by two parallel cylinders or a cylinder parallel to a plane, both representing wires or ground planes near high voltage conductors. These, and other simple geometrical configurations have very complex equations for the exact calculation of the maximum gradients. Simplified equations giving approximate solutions were developed by Bouers and Cath (reference 14.2) which are given in Table 8-8. Assuming an applied voltage of 10 kV and radii and separation distances of 20 mils (0.05 cm), maximum voltage gradients are also listed in this table for purposes of comparison.

Investigating the more common configurations in high voltage magnetics, those of parallel wires of equal diameter and a wire parallel to plane, the curves in Figures 8-27 and 8-28 were plotted. Assuming 1 kV voltage differences between the wires or wire to ground, and wire diameters as parameters, the log-log plot of separation distance versus voltage gradient is shown. Two 44 AWG wires 0.01 inches (10 mils) apart would have a voltage gradient at the surface of each wire of 250V per mil. For the ultrafine wire 56 AWG this gradient would be 550V per mil. Since parallel plate voltage gradient data given for encapsulation materials range from 400-500V per mil for puncture or breakdown, the problem is brought into focus when it is realized that the applied voltage between the wires could easily be 10 times, or 10 kV, which would result in a 10 times increase in the voltage gradient from the curves in Figure 8-27. Also these curves show that the increasing of separation is not as effective as might be expected. For example, if it was desired to have a maximum voltage gradient of 400V per mil for 10 kV applied to two parallel AWG 44 wires, the equation shows that the separation distance would have to be 154 inches. Thus it can be seen that other means than separation is required to reduce the voltage gradient between fine wires.

TABLE 8-8. SEVERAL ELECTRODE CONFIGURATIONS

CONFIGURATION		FORMULA FOR E	VOLTAGE GRADIENT	
			KV/CM	V/MIL
TWO PARALLEL PLANE PLATES		$\frac{U}{a}$	200	508
SPHERE AND PLANE PLATE		$0.9 \frac{U \cdot r + a}{r}$	360	914
TWO COAXIAL CYLINDERS		$\frac{U}{2.3 r \lg \frac{r+a}{r}}$	289	734
CYLINDER PARALLEL TO PLANE PLATE		$0.9 \frac{U}{2.3 r \lg \frac{r+a}{r}}$	260	660
TWO PARALLEL CYLINDERS		$0.9 \frac{U/2}{2.3 r \lg \frac{r+a/2}{r}}$	222	564
TWO PERPENDICULAR CYLINDERS		$0.9 \frac{U/2}{2.3 r \lg \frac{r+a/2}{r}}$	222	564
HEMISPHERE ON ONE OF TWO PARALLEL PLANE PLATES		$\frac{3U}{a} ; (a \gg r)$	600	1524
SEMICYLINDER ON ONE OF TWO PARALLEL PLANE PLATES		$\frac{2U}{a} ; (a \gg r)$	400	1016

U = 10 KV

r = a = .05 CM = .02"

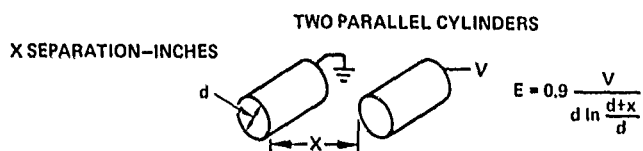
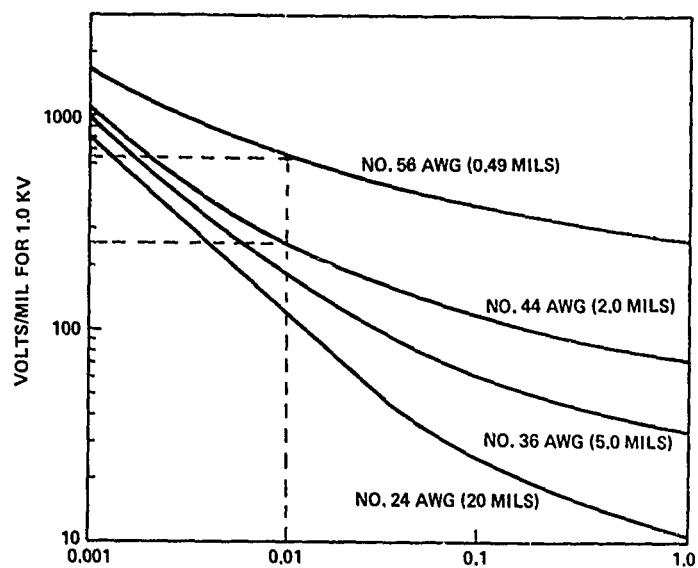


Figure 8-27. Voltage gradient variation, two parallel cylinders.

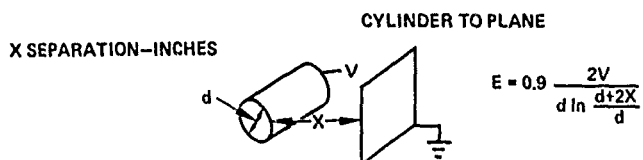
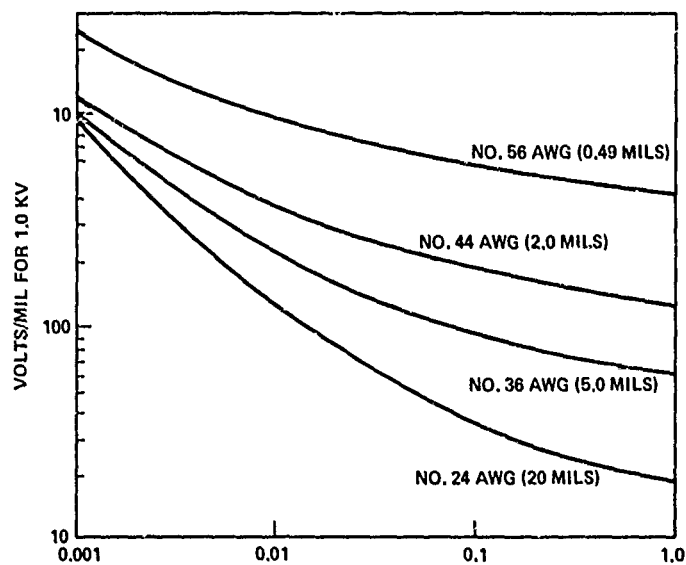


Figure 8-28. Voltage gradient variation, cylinder-to-plane.

A similar construction in Figure 8-28 shows that for a separation of 10 mils the voltage gradient for #44 wire to plane would be 875V per mil and for the ultrafine AWG 56, 950V per mil for 1000V between the wire and the ground plane. The voltage gradient for wire to plane is greater for the same distance than two parallel wires. As discussed in Section 10.1 gradient control can be achieved by appropriate use of equipotential planes on the bobbin itself. The above data and curves will serve as a guide to the designer and the manufacturing personnel in selection of wire sizes and routing of high voltage conductors.

8.5 METHODS OF MAKING LOW COST, HIGH RELIABILITY CONNECTIONS IN HIGH VOLTAGE COMPONENTS

The previous section was concerned with wire selection and routing to achieve voltage gradient control in high voltage magnetic components. The approach was based on knowing and appreciating the problem of voltage gradient control; this section is concerned with the problems involved in achieving connection of the fine wire of the transformer winding with the outside world. This includes wire terminations, terminals, and achieving encapsulations that are void-free.

8.5.1 Voids in Encapsulation Materials for High Voltage Magnetics

Prevention of the occurrence of voids during the encapsulation operation and subsequent functioning in test and field conditions is a prime requirement for achieving high reliability in high voltage magnetic components. The problem of a void is that it introduces a region of low dielectric strength, about 30V per mil, in an otherwise solid encapsulation compound with voltage gradients of hundreds or even thousands of volts-per-mil. This low voltage gradient makes it susceptible to generation of corona discharge which can eventually erode the insulation, make the void larger, and eventually cause an arc-through or voltage breakdown of the insulation itself. Detection of the presence of voids is the purpose of applying high voltages to the conductors and using sensitive pulse detection equipment to pick-up low level corona discharge. In this way, it is hoped that an adequate test will detect the presence of voids and cause rejection of the part before it fails subsequently in the field.

Voids can be due to a variety of causes. The obvious one, of course, is trapped air or bubbles in the winding during the encapsulation phase. Bubbles are hopefully eliminated by evacuating the components of the encapsulants under vacuum, pouring in vacuum, then applying pressure up to 500 psi to the component during the curing phase so as to compress whatever remaining bubbles into an extremely small volume. Success of these procedures can only be evaluated during the high voltage testing phase. Another source of voids is the lack of adhesion between two materials, e. g., the copper wire and the encapsulation compound, because they have widely different thermal expansion coefficients. Initially, the material may have adhered to the wire, but subsequent temperature cycling caused a differential expansion and shearing action resulting in a pulling away of the encapsulation compound from the conductor, providing a lack of adhesion which results in a void. This can initiate the corona inception problem noted above. Another source of voids is internal fractures occurring in the encapsulation due to thermal stresses.

A generally unappreciated source of insulation deterioration is the actual creation of voids where none existed before by extremely high voltage gradients, as noted in reference 14.3. By electro-polishing techniques, needle points of very sharp curvature were encapsulated in encapsulation compounds and shown initially to have no voids around the tip. However, application of sufficient voltage to the needle caused a void to appear at the point followed by "treeing" through the insulation, resulting in destruction of the material.

8.5.2 Voltage Gradients at Ends of Cut Wire

A possible source of unanticipated high voltage gradients is the ends of wire, cut by conventional cutting tools, being embedded in the encapsulation, during the terminating or joining to intermediate lead wire operation. Accordingly, samples of AWG 36, 48, and 54 magnet wire were cut with a typical diagonal cutting pliers and the ends of the wire photographed with the scanning electron microscope (SEM) as shown in Figures 8-29, 8-30 and 8-31. Assuming the end of the wire to be a hemispherical representation of an isolated sphere as shown in Figure 8-26b, the gradient in volts-per-mil was



Figure 8-29. AWG-36 cut by diagonal cutting pliers.

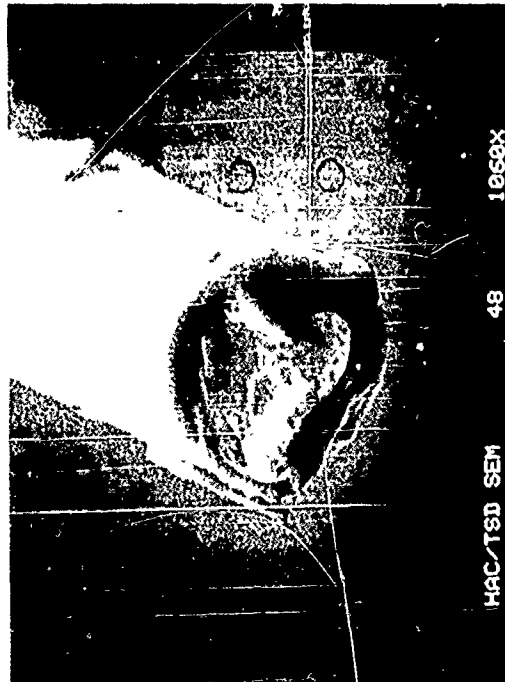
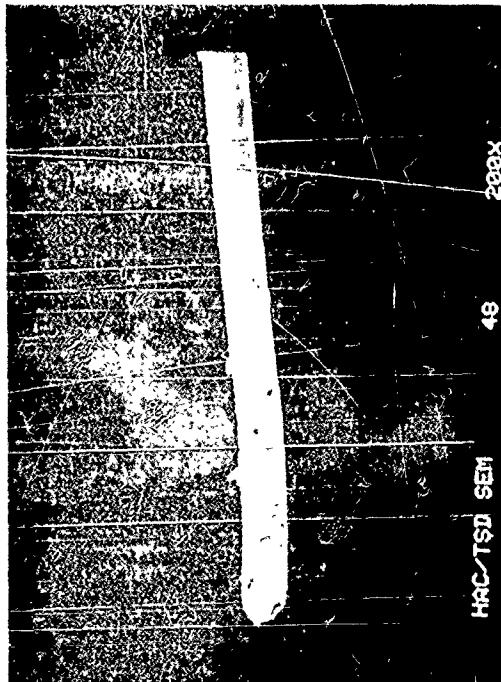
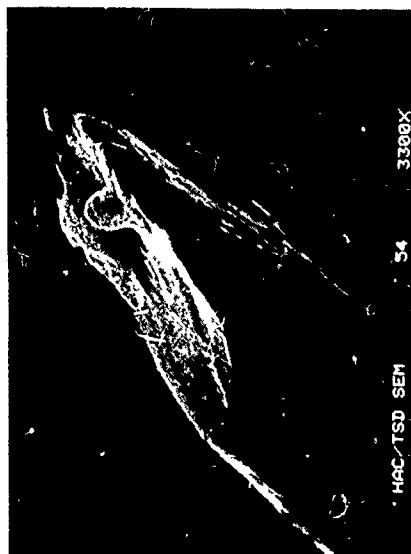
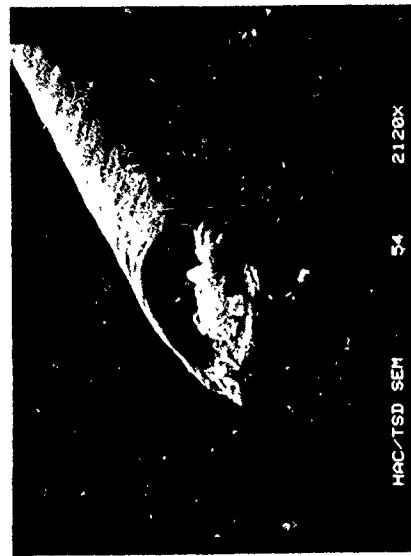
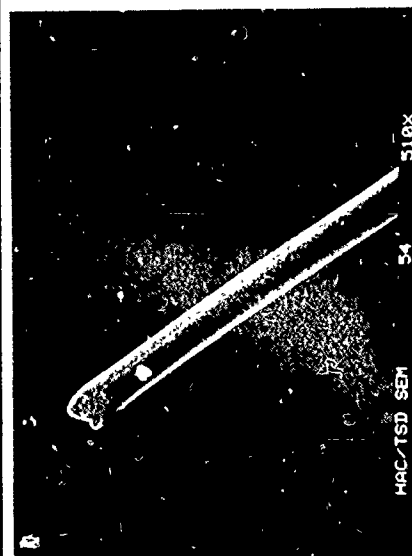


Figure 8-30. AWG-48 cut by diagonal cutting pliers.

AWG 54 MAGNET WIRE CUT WITH DIAGONAL CUTTER

HUGHES



REDUCED TO 80%

Figure 8-31. AWG-54 magnet wire cut with diagonal cutting pliers.

calculated for 1000V applied to the wire and shown in the third column of Table 8-9. As can be seen, the voltage gradient varies from 357V per mil for AWG 36 to 3200V per mil for AWG 54. However, the crushing of the wire by the diagonal cutters produces a much sharper and smaller diameter protrusions, the diameters of which were measured and recorded in column 4 of Table 8-9. A very rough estimate shows the range from 1.2 mils diameter to 0.031 mils diameter. This corresponds to a voltage gradient per 1 kV of 1700 - 63,000 as tabulated in column 5 of Table 8-9.

To see if the shearing action produced by a new pair of scissors would result in less gradients than the diagonal cutters with their crushing action, other samples of the same sizes of wire were cut and observed with the SEM and are shown in Figures 8-32, 8-33 and 8-34. It can be seen from Table 8-9 that the voltage gradient increased markedly for the larger wire size, but decreased very appreciably for the ultrafine wire. Since these are very rough measurements, the gradients calculated are only estimates.

A significance of these large gradients can be appreciated because in calculations based on information in reference 14.3 shows that the approximate voltage gradient necessary to initiate the formation of voids in encapsulation materials that the experimenter tested was of the order of 35,000 -

TABLE 8-9. END-WIRE VOLTAGE GRADIENTS/KV ISOLATED SPHERE APPROXIMATION

WIRE GAUGE AWG	NOM DIA MILS	WIRE HEMISPHERE V/MIL	DIAGONAL CUTTERS		SCISSORS	
			PROTRUSION DIA MILS	GRADIENT PER 1 KV V/MIL	PROTRUSION DIA MILS	GRADIENT PER 1 KV V/MIL
36	5.6	357	1.2 1.3	1700 1500	.33 .47	6000 4200
48	1.4	1400	.06 0.1	33,000 20,000	.47 .72	4200 2800
54	.62	3200	.083 .031	24,000 63,000	.12 .12	17,000 17,000

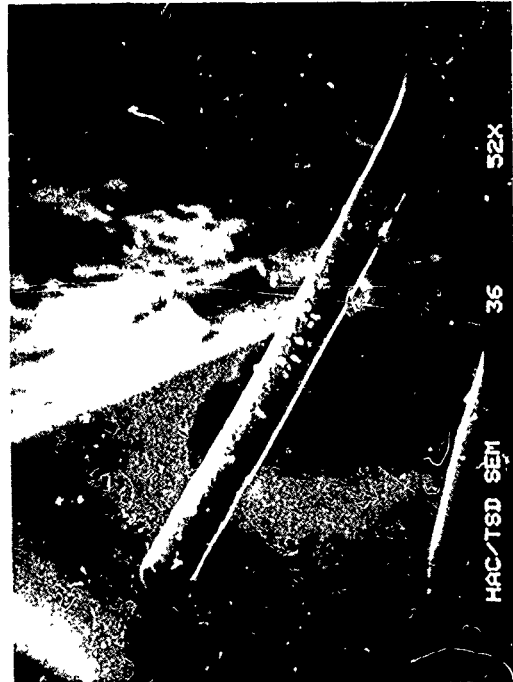


Figure 8-32. AWG-36 wire cut by new scissors.

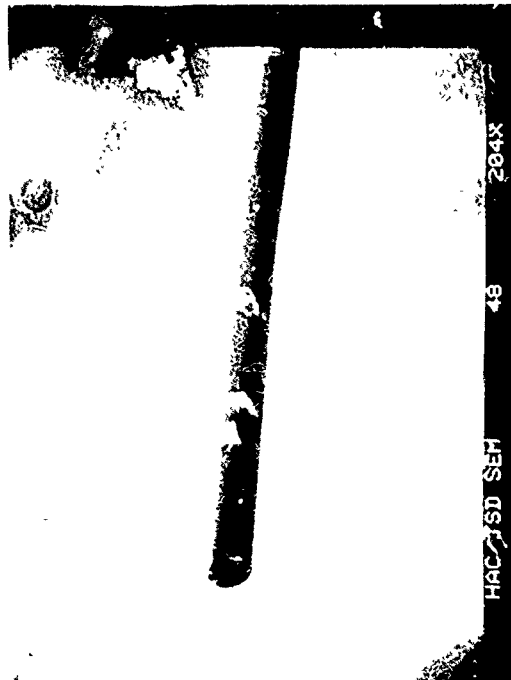
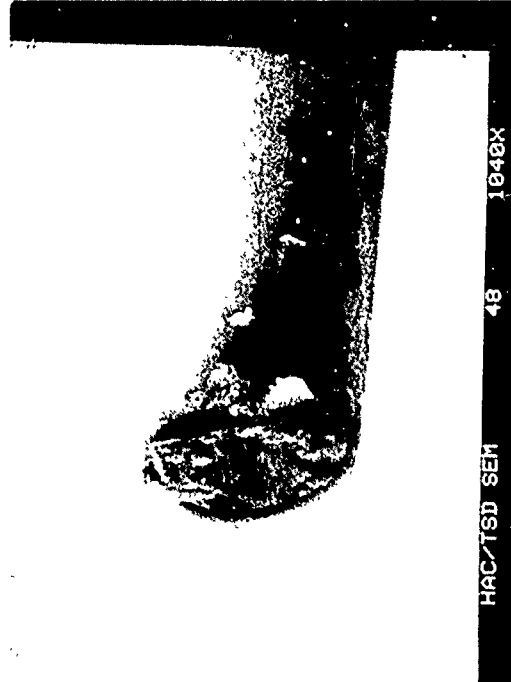


Figure 8-33. AW 48 11.3 cut by new scissors.

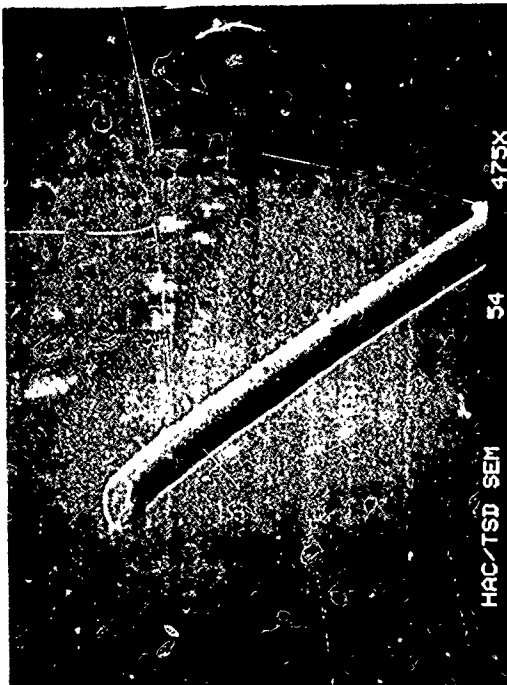
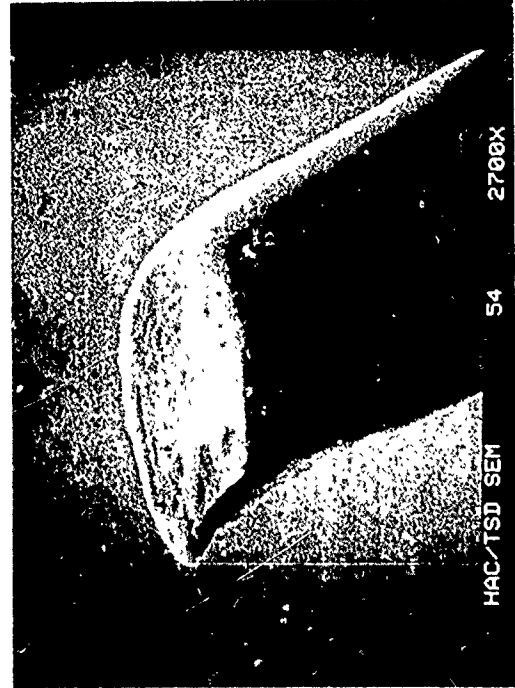
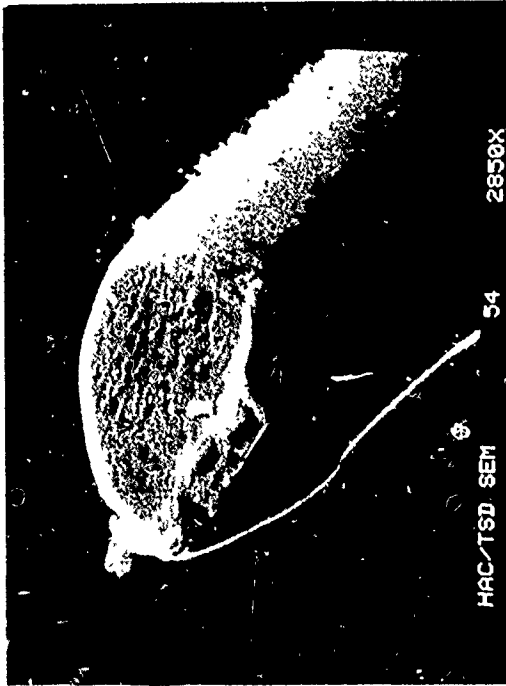


Figure 8-34. AWG-54 wire cut by new scissors.

50,000 V per mil, well within the magnitudes of the smaller wire sizes measured in Table 8-9.

8.5.3 Reduction of Gradient at Ends of Wire Termination

This problem of high gradients in insulation due to sharp points on the cut wires can be eliminated by carefully solder balling the end of the connection to the intermediate wire and the fine wire. However, this requires excessive amount of heat from the soldering iron and, in addition, the possibility exists that the fine wire might be dissolved by the solder. A better method would be the use of a small, hollow conductive bead on the end of the wire which would shield the sharp point from the insulation. A source of conductive spheres could not be found other than very small gold ones fabricated by jewelers.

To show the configuration, the balls from a ball chain drive, 0.125" diameter were the smallest conductive ones found available. Figure 8-35 shows ball termination of AWG 52 to an intermediate lead of AWG 26. Using this sphere approximation, the voltage gradient of the surface per 1000V is calculated to be 8 volts-per-mil. Smaller conductive spheres, of the order of 50 mil's diameter, would result in a 20V per mil per 1000V. With a little practice the handling of such small spheres and inserting them on the ends of the wire terminations should not be too difficult for trained personnel.

For the higher voltages, the diameter of the spheres should be such that the maximum voltage gradient of the surface be of the order to 200-400V per mil. The surfaces of the sphere should be scrupulously clean and grit-blasted to provide a good bonding surface. The spheres do not need to be metallic; they could be fabricated from conductive plastic materials with high resistivity, since only an equipotential surface is desired to be formed and no current flow exists. Silicone molds were fabricated to make small diameter plastic spheres from Epon 825 loaded with a material to provide a degree of conduction. It was planned to use copper filings, silver paste and graphite as the conductive material, but the amount needed made the materials so thixotropic it was far too viscous to be inserted into the mold and provide the smooth spherical surfaces required.

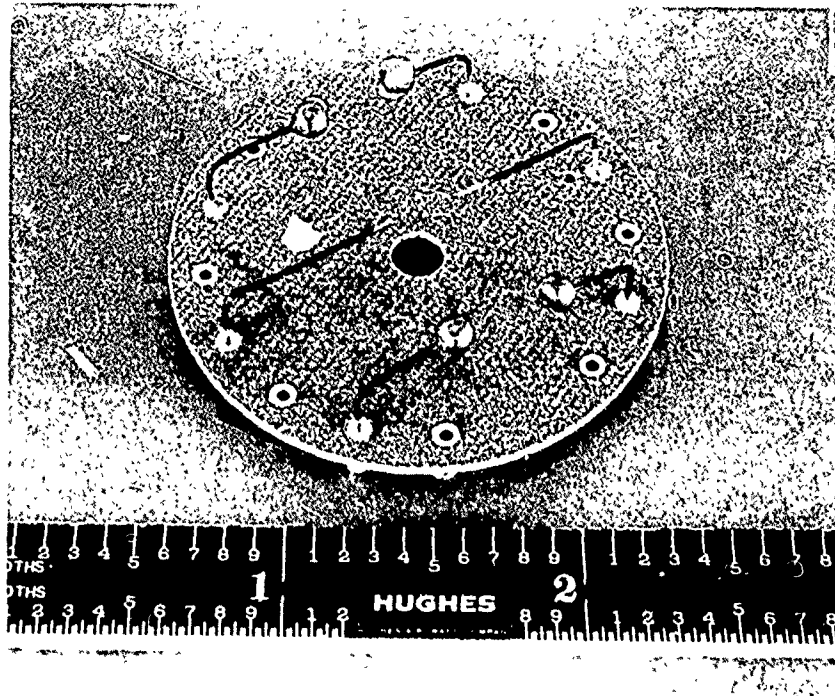


Figure 8-35. AWG soldered to intermediate lead AWG with and without ball termination.

Procurement of small spheres, either of plastic or hollow metal, smaller than 1/8 inch bead chain were not successful, except in the jewelry trade. Their jewelers make hollow gold spheres much smaller in diameter, but these were not considered practical for the application.

8.5.4 High Voltage Terminals

Swage terminals for high voltage applications have been redesigned to provide a smooth contour with a spherical end for the purposes of gradient reduction. However, the problem of the voltage gradient at the swaged end, which can result in feather-like projections or protrusions similar to that of the cut wire noted above, can result in a very high gradient. What is much worse is that this gradient concentration occurs at a interface between the encapsulation compound and the terminal board which can separate, creating a void. One solution to remove the maximum gradient location away from

the encapsulation-terminal board interface is by the use of disc washers with rolled edges underneath the swage. These effectively shield any sharp points occurring during the swaging operation and also remove the high gradient away from the interface as can be seen in Figure 8-36. A complex forming die would be required to preform this corona ring, which was not within the scope of this program, so a simple dishing punch was fabricated to achieve the same result with solid brass washers, without success. Further work needs to be done.

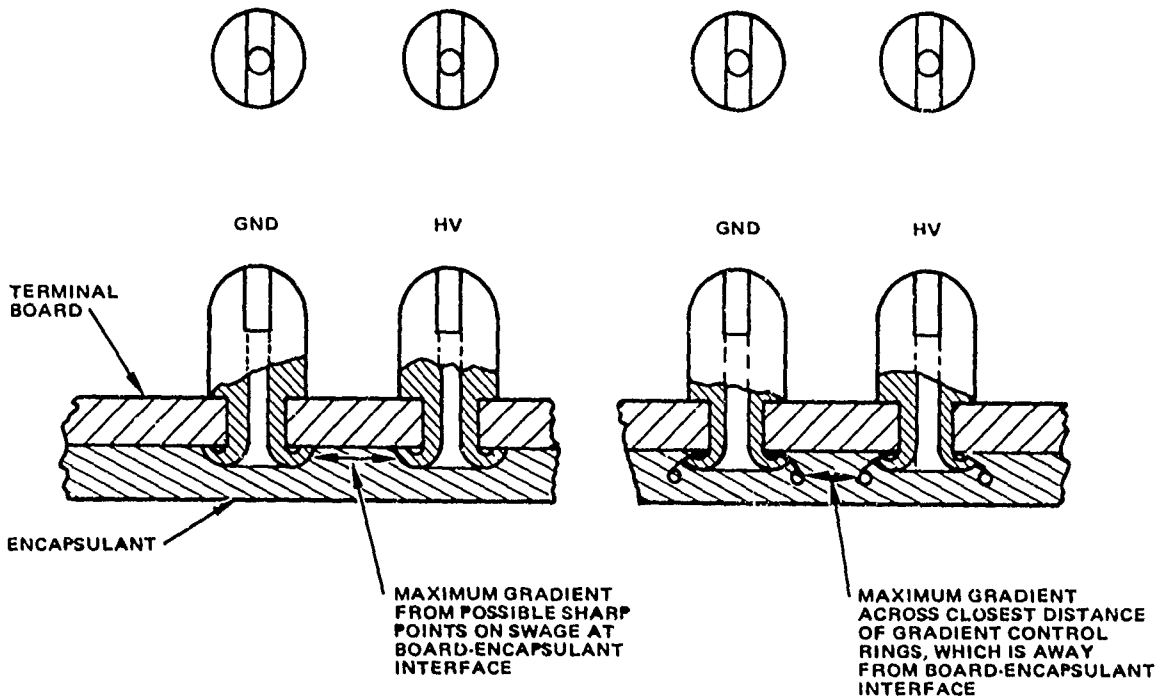


Figure 8-36. High voltage swage terminals, with & without gradient control rings.

9.0 TOOLING AND EQUIPMENT FOR ENCAPSULATION OF ELECTROMAGNETIC DEVICES

The objective of this task was to evaluate the tooling and equipment required for encapsulation of electromagnetic devices; determine feasibility of using automatic mixing and metering equipment; and, based on these results, implement a continuous process for encapsulation to replace the conventional batch-oriented processes used by many vendors for high reliability transformer and inductors for missile systems. Based on the materials selected as being optimum for missile applications from Section 3.0, Volume I, this task is concerned with the selection, evaluation and design of molds and molding equipment associated to provide a continuous operation in the context of missile systems applications. First of all, it is recognized that transformers and inductors for missile systems applications will never be in the quantities that exist for similar devices for commercial applications, such as television or high fidelity amplifier systems. Based on these considerations, the following assumptions and constraints were made.

1. Only magnetic components with cores were considered in this program. This would eliminate air core inductors and transformers.
2. Void-free encapsulation is the ultimate objective of this program. It is recognized that low voltage components can tolerate voids or bubbles; such is not the case for high voltage. Blown and syntactic foams were not considered as an encapsulation material in Section 3.0, Volume I and, consequently, are not used in this task.
3. In the context of missile applications, low production quantities are considered of the order of hundreds per month; medium production, thousands per month; and high production would be ten thousand or so per month.

4. Every effort will be made in mold design and process execution to minimize labor, especially in the cleaning up of the component and the molds.
5. The molds shall be designed so as to provide a finished outer surface requiring no further finishing labor. In other words, potting cups and covers shall not be used. Terminal boards required for the termination of the connections to the coils and interfacing with the outside world are permitted.
6. Transformer or inductor designs representative of actual missile components and, if possible, the one selected would have already been ordered in production quantities so that the anticipated cost of the new ways of production would allow a comparison.
7. The components selected should be representative of a toroid and a C-core with bobbin configuration, have multiple windings, some of which would have fine wire.
8. Minor modifications of the component packaging would be permitted to facilitate and simplify the use of molds in the production operation.

9.1 MOLDING TECHNOLOGY EVALUATION

Three techniques are used by Hughes Aircraft Company to encapsulate parts. These are: vacuum form molds, slush molds, and simple aluminum molds. The techniques of vacuum forming and slush molding are well known and will only be covered briefly here.

In the following paragraphs, the present techniques are described as a jumping off point for describing the results of the MM&T investigations. Simple aluminum molds are comprised of several pieces of metal which are fabricated to provide a mold of the proper configuration for encapsulation of the part.

All of the above three techniques are required to be used in situations where the encapsulation material is poured in vacuum and then during the curing phase a pressure of up to 500 psi is applied to compress the voids or bubbles into small sizes. Obviously, the molds used with these three techniques at Hughes do not have the physical strength to withstand the vacuum and pressure; consequently, a heated pressure chamber or pressure pot is required for the vacuum pouring and pressure curing of the material. For the MM&T program, individual aluminum molds designed as pressure vessels were fabricated as described below.

9.1.1 Vacuum Forming

Vacuum forming molding is a process which provides a thermoplastic film which forms and encloses the part to be encapsulated by means of vacuum, which conforms to the outline of the part. The surface finish of the part is a satin finish which is due to the flat finish of the polypropylene vacuum form film that is used in the molding operation. Intended for only low quantity production, this technique is heavily used in applications where the amount of unsupported resin must be minimized.

The major problem with this method is that the vacuum formed part must be carefully broken out of the enclosing matrix without causing a fracture to extend within the vacuum form. Another problem is that the thickness of insulation over the windings is not directly controllable because of the vagaries of the hot film as it collapses over the part.

The vacuum forming approach was dropped from further consideration for MM&T because of the difficulty in maintaining the desired thickness over the winding, the amount of hand labor required to retrieve the part from the encapsulation, and its cosmetic appearance.

9.1.2 Slush Molding

The slush mold technique involves the production of expendable, meltable, molds which are formed out of low temperature molten metal by the insertion of a cold metallic "master." This molten metal, being composed of various low melting temperature metals, expands slightly upon solidification, providing a faithful representation of the surface of the master. The master is removed, mold release applied, the part is then inserted. Encapsulant is poured in and cured, whereupon the mold is peeled off, tossed into the pot and reused.

The slush molding technique was investigated because it appeared to have possible application to low production and perhaps medium production quantities. Only the toroidal configuration was considered for the application of the slush mold technique. To facilitate indexing of the mold, the terminal board diameter was increased so as to index the part in the mold. This simplified the mold design and if the small protrusion of the terminal board was undesirable a simple trimming operation could be used.

Two slush mold masters were fabricated, one of which is shown in Figure 9-1. The mold masters were given a high polish for two reasons: first, the molds would be more easily removed and, secondly, a high polish on the inside of the mold was desired to give a smooth exterior to the finished part.

The use of slush techniques as a direct mold for the toroidal parts did not work as well as expected. For unknown reasons, the hard polish of the master did not provide a smooth mold surface. It was difficult to remove the slush molds from the master. After encapsulation, removing the slush mold from the part required that it either be dipped into the molten pot of metal or heated on a hot plate until the metal melted away. In either case the part was subject to possible heat damage because it had an intimate thermal contact with the exterior surface of the part. Thinking that the lack of a good surface might be due to the presence of contaminants in the molten metal, new materials was ordered; however, the surface finish was not improved. Advances made in the use of silicone molds resulted in no further work being done on this approach.

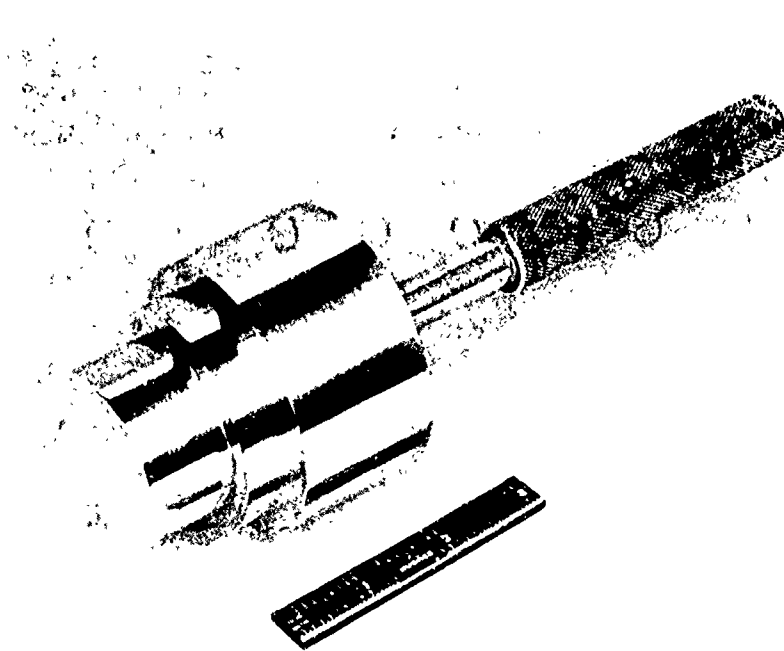


Figure 9-1. Slush mold master.

9.1.3 Silicone Rubber Molds

Silicone rubber molds proved to be feasible and useful in the molding of the parts for low and medium production rates. It was estimated that with care in handling, each silicone rubber mold could produce 100 or more finished parts.

Using Silastic J mold making silicone rubber, a core of the same physical dimensions as the finished part was fabricated. Figure 9-2 shows the core and mold. The bottom of the core was formed using an aluminum plate which had been machined with the proper holes and other features. The sides of the core were formed using a plexiglas cylinder of the same inside diameter as the diameter of the finished part.

The final mold was made using a two step process. The bottom of the mold was made in the first step. The master was placed in a 3/4 inch deep layer of silastic J so that approximately 3/8 inch of rubber was between the master and bottom of the mold.

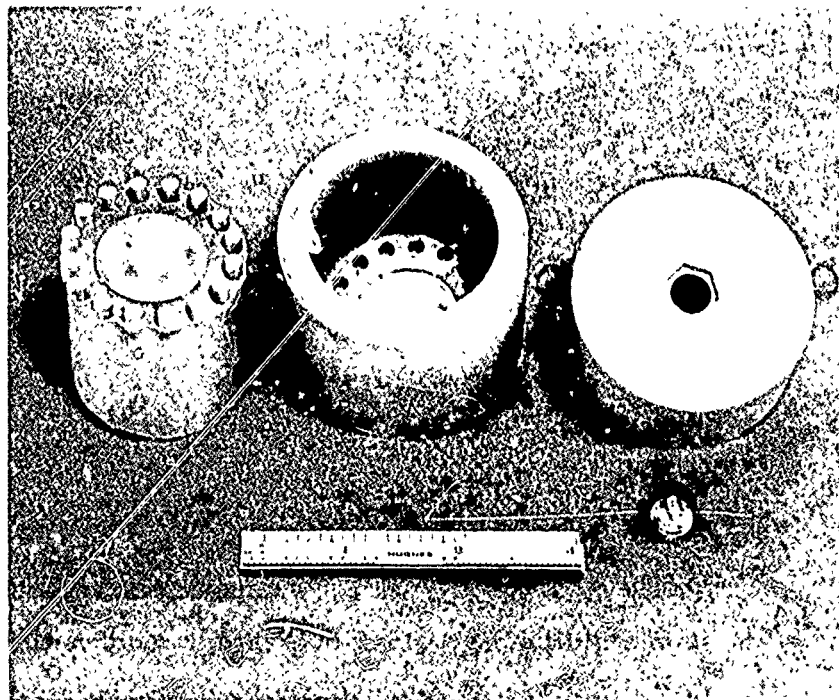


Figure 9-2. Silicone rubber master and molds.

The second step was to fabricate the wall of the mold by means of a plexiglas cylinder whose outside diameter was the same as the diameter of the master. It was centered upon the mold bottom and secured to it using tape and RTV-11 on the inside of the cylinder. A second, larger plexiglas cylinder was placed coaxially about the inner cylinder and secured on the outside with tape and sealed with RTV-11.

At the start of the investigation, the first rubber molds were cured in the oven at both ambient pressure and temperature. When these molds were exposed to 500 psi during the pressure cure cycle of the encapsulated dummy part, a rough surface appeared on the surface due to the presence of internal voids in the rubber which compressed under pressure. Figure 9-3 shows the dummy part before and after encapsulation, which resulted in a rough surface due to the pressure cure. To overcome this problem, new rubber molds were cured at 500 psi at ambient temperature which then resulted in smooth surfaces for the encapsulated components.

Flash removal was facilitated as hand labor minimized by the application of quick-curing RTV-11 with Nuocure 28 to the terminal holes just

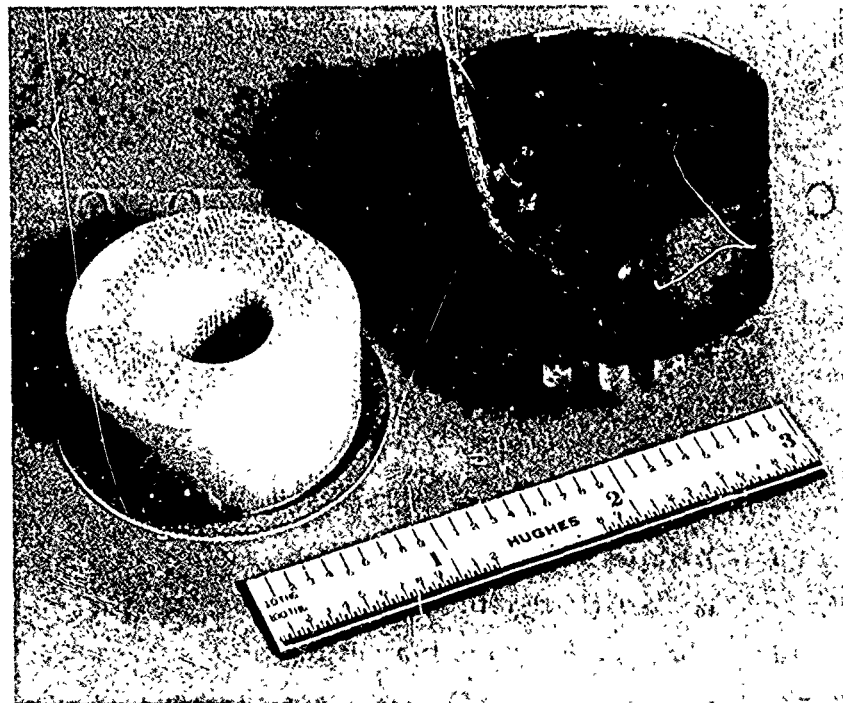


Figure 9-3. Encapsulation of dummy part showing surface roughness.

before the part was placed into the mold. This technique virtually excluded all of the encapsulant seepage into unwanted regions, and the part was restrained from moving when the resin was initially poured in the mold.

One problem with the rubber mold was extracting the finished part. Initially, the part was pushed from the mold using a small arbor press. This required some manipulation of the mold and blocks upon which the mold edges were placed so that the part could be extracted without damage to the mold itself. Investigation showed that one of the major forces holding the part in the mold was the internal vacuum between the bottom of the part and the bottom of the mold. A method to more easily remove the part was found by a redesign of the mold to include an O-ring sealed plug in the bottom of the mold. This plug was liquid tight when the encapsulant was poured. Removal of the plug after curing the part could easily be removed using low pressure air which caused the mold to bulge slightly, releasing the part. This plug is shown in the right hand silicon rubber mold in Figure 9-2.

9.1.3.1 Pressure Curing of Rubber and Slush Molds

In order to use the rubber molds in a high pressure curing process, such as that required with Epon 825/HV, pressure pots are needed. A major disadvantage in most commercially available pressure pots is their large size. A small pressure pot, capable of withstanding 500 psi for long periods of time, was fabricated and tested to the ASME pressure vessel standards. This pressure vessel was small and portable. The three sections were held together using high strength steel bolts. Pressure integrity was maintained using Viton O-ring seals. Viton seals were used rather than copper O-rings because the vessel was expected to handle temperatures only up to 125°C. If the Viton O-ring had showed any sign of deterioration copper O-rings would have been used.

The vessel was somewhat tedious to open or close; however, the vessel was able to be heated and could be easily pressurized.

The usual procedure is that the encapsulant was poured into the mold's separate vacuum chamber. The filled mold is then placed in the small pressure pot. The pressure pot could be evacuated with a separate vent to admit the resin so that pouring of the encapsulant could take place in

the pressure pot itself with the use of a tube through the interface into the mold. This technique lends itself especially well to mass production, as several small pressure pots, with high pressure nitrogen and vacuum plumbing, and with automatic metering and mixing equipment, provides a continuous process where transformers of various sizes and shapes may be included.

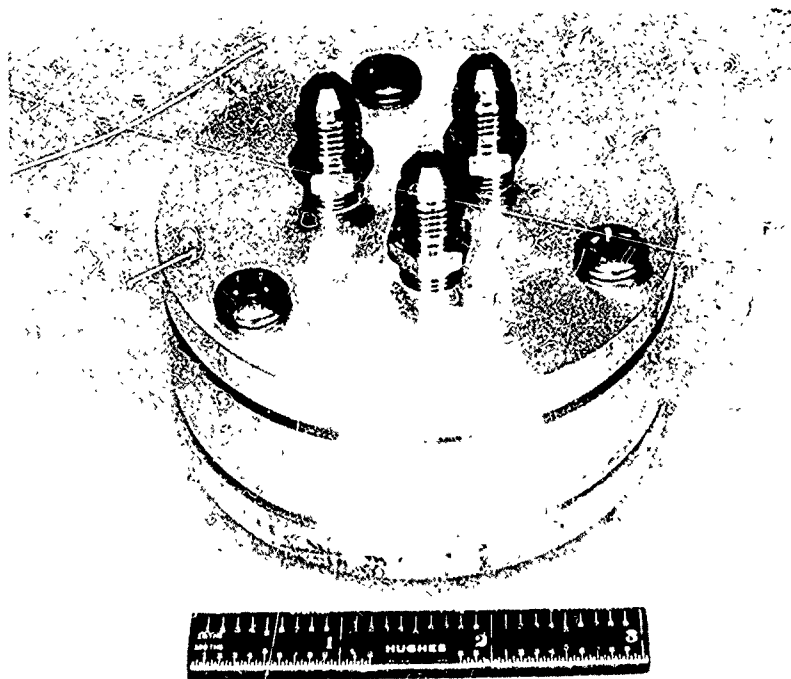
9.1.3.2 Centrifuge Substitution for Pressure Cure

An alternate approach to the 16-hour cure of Epon 825/HV at 500 psi was evaluated using the silicon rubber molds. The resin was vacuum outgassed, then poured into the molds at ambient air pressure. The molds were then centrifuged from 5 to 10 minutes, removed and placed into an ordinary temperature oven for the final cure.

The penetration appeared to be complete as sectioning showed no apparent voids. High voltage components, however, tested for corona inception voltage showed that the pressure cure seemed to be better than the centrifuge for removal or elimination of bubbles and voids. The main disadvantage of using a centrifuge is that the samples placed in the centrifuge must be balanced very closely so that undue vibration is not caused. This is not really a problem because counterweights can be added to compensate for the variations in weight. Catalog data on one centrifuge showed places for six samples at once. Further work needs to be done to prove out this system, but if it could be done in place of the 16-hour cure, a tremendous savings in time and expensive capital equipment could be achieved.

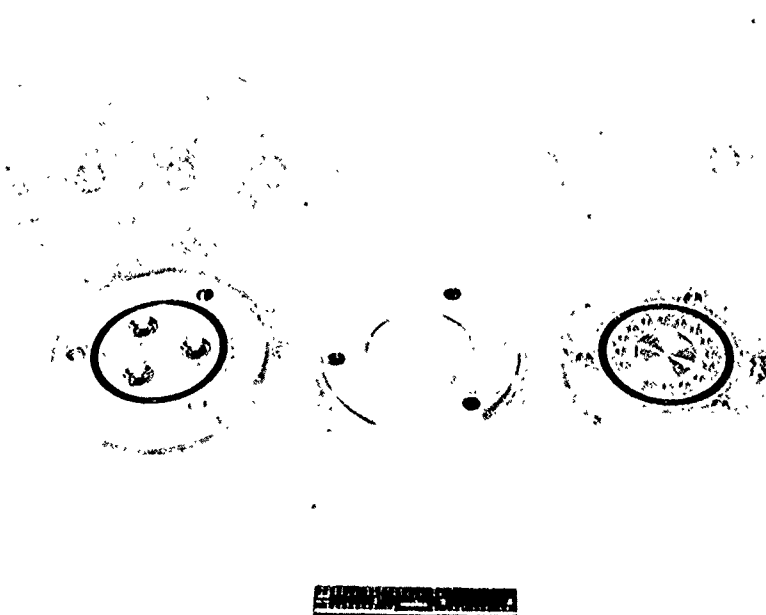
9.1.4 Aluminum Pressure Molds

In order to eliminate the use of a pressure pot for vacuum pouring and curing under 500 psi pressure, aluminum molds of simple construction were designed for the MM&T program which would not only mold the part, but would serve as a self-contained pressure vessel. The basic idea was that with one small mold a complete vacuum, resin filling, and pressure chamber system would be available. Figures 9-4 and 9-5 show a photograph of the aluminum mold assembled and disassembled, respectively. The fittings on the top are for the vacuum line, resin filling line, and the air pressure line. As can be seen, the mold consists of three simple pieces.



06928-08

Figure 9-4. Aluminum pressure mold.



06928-08

Figure 9-5. Aluminum pressure mold, disassembled.

The base had provision for insertion of the transformer terminals and an O-ring grooved to contain the pressure in the vacuum. The center section served as a mold for the part, and had highly polished ends to provide a seal for the O-rings. The top plate contained inlets for the resin, air, and vacuum.

An example of an early fabricated toroidal transformer is shown in Figure 9-6 before and after encapsulation in the aluminum mold. The smoothness and clarity of the encapsulation is evident.

Parts fabricated from this mold and design were found to have depressions resulting from the high pressure nitrogen during the 500 psi cure. A solution to this is to provide a large conical shaped cut-out in an intermediate plate so as to provide a reservoir for the resin. The reservoir should be large enough so that when the high pressure nitrogen is applied to the resin the depression formed does not extend to the part but only partially

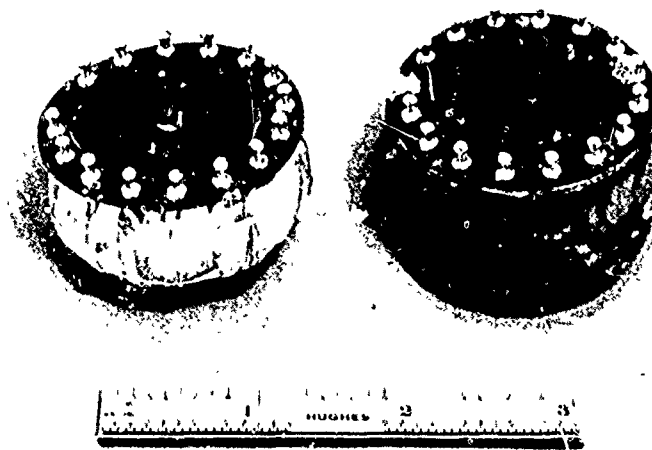


Figure 9-6. HV toroidal transformer before and after encapsulation.

through the reservoir. There should be a separate, small cylindrical passage through the plate for the vacuum connection in order that the mold can be evacuated before pouring so that during pouring the part is impregnated under vacuum.

9.1.5 High Production Rate Molding Equipment

The previous sections of this task have been concerned with production considerations of low to medium quantities of electromagnetic components. Within the context of "high quantity production for missile system applications" (Section 9.0, subparagraph 3), high production molding technology employed in the fabrication of plastic items for general usage was investigated in this MM&T program. This technology is usually characterized by large, multi-ton presses which accommodate replaceable mold inserts to form the plastic parts at a high rate. The mold inserts, usually multicavity for the smaller parts, are designated to interface with the resin feed lines and metering equipment which provides the proper quantity of material after the mold is closed by the press ram. The plastic material is usually introduced into the mold at a low pressure, then brought to a high pressure, which the press must be designed to withstand. After a cure time for solidification of the material, sometimes of the order of seconds, the press is retracted, mold opened, the part removed, and the process repeated. Obviously, the large capital outlay for the press and mold costs must be recoverable during the production runs for such an approach to be economically feasible.

Processes investigated included transfer molding reaction injection molding (RIM) and liquid injection molding (LIM).

9.1.5.1 "C" Core Coil Molding Process

The majority of the technical effort of this task was placed on the "C" core molding task. An existing mold base from a previous IR&D effort in the field of Liquid Injection Molding (LIM) was utilized, in conjunction with a cavity insert set modified to produce the desired "C" core configuration as shown in Figure 9-7; Figure 9-8 shows the vertical transfer press.

The system thus utilizes 1) An external source of mixing and resin introduction, 2) a transfer press, 3) a standard mold base with vacuum access and 4) the appropriate mold cavity inserts. Figure 9-9 shows the mold cavity inserts as they are ejected from the mold base.

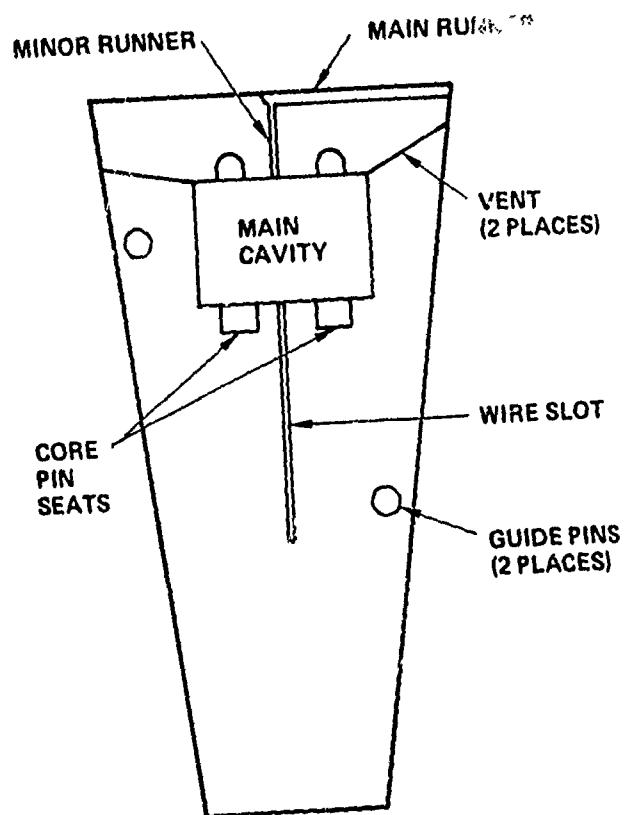


Figure 9-7. "C" core coil mold cavity insert.

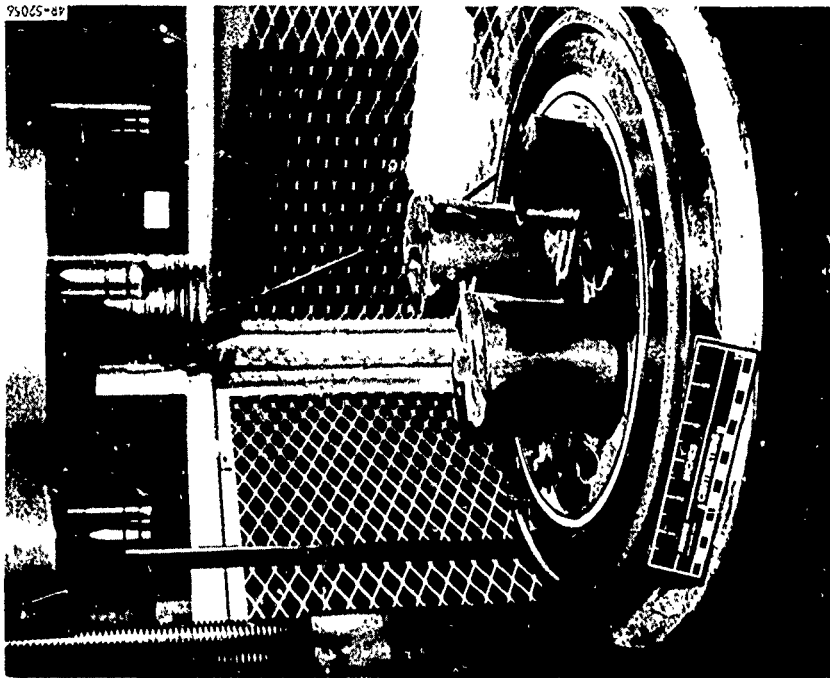


Figure 9-9. Ejection of mold inserts from mold plate.

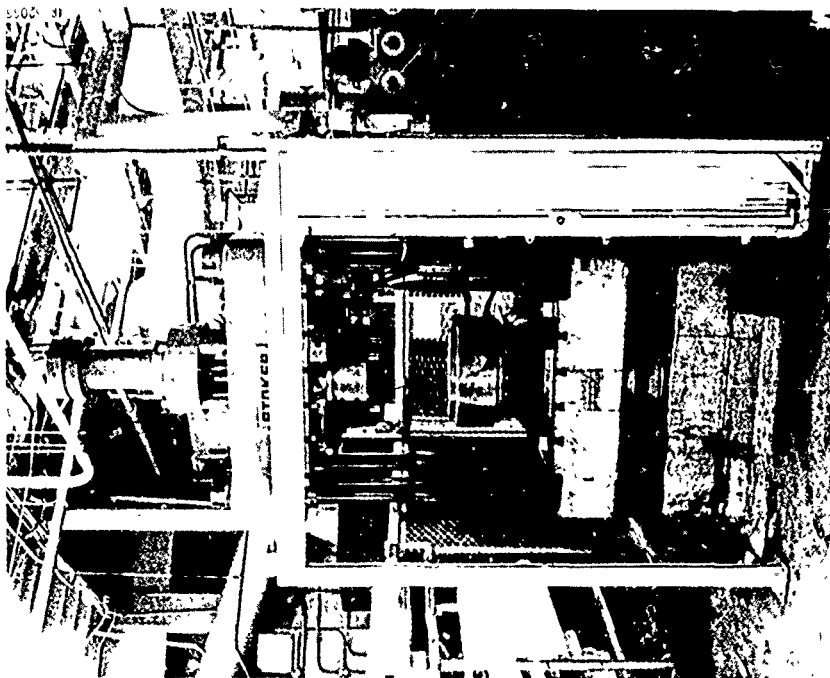


Figure 9-8. Vertical transfer press.

1. Resin Selection. The resin chosen for this task was Epon 825/HV. While the "HV" catalyst system was originally developed at Hughes, it is available commercially from outside sources. The resin formulation is as follows:

Epoxy: Epon 825
Hardener: HV

Mix Ratio - Epon 835 100 PBW
 HV Hardener 18 PBW

HV Hardener Mix

Menthane Diamine 125G
Metaphenylene Diamine 50G
Benzyl Dimethylamine 0.75G

Several factors influenced the choice of this particular system. First, material evaluations conducted as part of this same MM&T program concluded that, on the basis of available data, this system represented the most desirable combination of end product properties. Second, since the system was in widespread use within Hughes as an encapsulation resin, a broad background information base was available. In addition the system has been used in past LIM studies within Hughes and thus, personnel were familiar with its handling and processing characteristics.

2. LIM Processing. The LIM process was selected for investigation for its unique combination of technical characteristics and its applicability to mass production techniques. One of the major problem areas encountered in several previous programs at Hughes of adapting mass molding techniques to electronic components was that of "wire wash", particularly occurring in fine wire devices due in part to fluid drag, molding pressure and melt viscosity. By utilizing a LIM approach, an encapsulating resin system of low viscosity can be employed. This, in conjunction with injection under vacuum pressure only, should result in a system with minimal fluid drag and hence, minimal wire displacement. Final molding pressure can then be applied to the essentially hydrostatic system with little probability of component damage even with pressures of 200 psi. In addition to minimizing fluid drag, the low viscosity resin system also facilitates penetration of the multiple layers of wire and tape in order to minimize voids in the finished component, and hence decrease reject rate.

Since the process involves hard tooling of fixed dimensions, the ability to couple with automatic mixing/metering equipment and press controlled cycles, LIM can provide a controllable, repeatable mass production process and negate the operation sensitivity of most hand production encapsulation processes.

3. Procedure. The molding process developed in this task is outlined below:
- a. Prepare mold and bakeout components.
 - b. Insert components in cavities, insert cavities, and heat to 212°F.
 - c. Close mold and evacuate (20-23 in Hg) for 1 hour.
 - d. Heat resin components at 180°F, degas resin before adding hardener, load resin.
 - e. Inject resin, continue to pull vacuum on mold for 10 min., then allow further 10 min. residence time without active vacuum.
 - f. Activate transfer ram, cure under pressure 4 hours at 212°F
Clamp pressure 100 tons
Ram pressure 2000 psi
 - g. Cool and remove.

Notes:

Step a: Mold treated with RAM 87-X. Bake on mold release and oversprayed with MS 22 mold release just prior to insertion of component.

Component bakeout in vacuum oven to remove absorbed H₂O and other contaminants which could result in voids in the final part.

Step c: Necessitated by mold configuration available for this work. Could be greatly reduced in optimized cycle with appropriate equipment.

Step d: Standard procedure to minimize dissolved gases in resin, sequence necessitated by vacuum sensitivity of catalyst.

Step e: For reasons as stated above, plus provide driving pressure to fill cavity.

Step f: Could be significantly reduced in optimized cycle. Cavity pressure monitors indicate that gellation is probably complete at 30 min.

A number of "C" core coils were produced with the described process. The mold insert, and a "C" core coil part before and after molding, and the completed inductor with a banded "C" core is shown in Figure 9-10. Several of these components were sectioned and examined microscopically for voids. In almost all cases, they were found to be essentially void free. Due to program limitations, the electrical characteristics of these components were

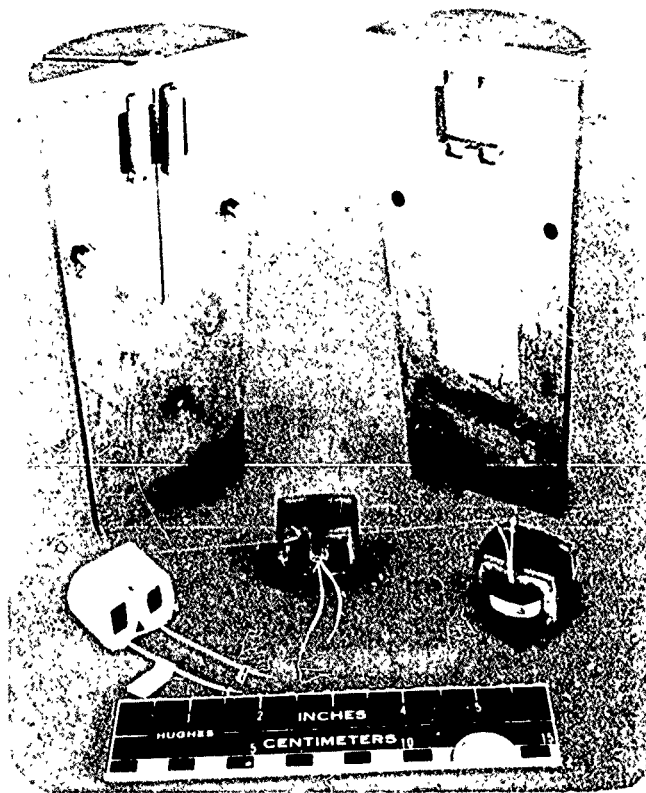


Figure 9-10. LIM molded dual coil for "C" core inductor.

only cursorily investigated, although initial indications were that they were equivalent in performance to acceptable "high-rel" parts.

9.1.5.2 Toroidal Coil LIM Molding Process

Concurrent with the "C" core coil molding investigation, a contract was issued with a LIM equipment manufacturer to design, fabricate and test a mold for the toroidal configuration which would interface with a horizontal transfer press, available in his experimental laboratory. Unanticipated delays in completion of the toroid LIM mold caused the program to be suspended so that the report deadlines could be met. A molded transformer together with disassembled mold is shown in Figure 9-11.

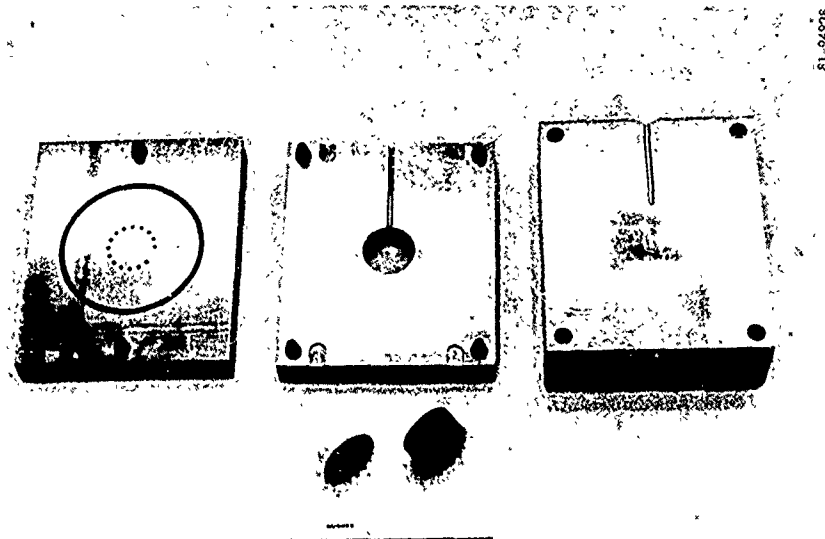


Figure 9-11. Toroidal coil LIM mold, coils before and after molding.

An X-ray photograph of this transformer revealed a displacement of the winding to one side, compared to an uncapsulated sample, as shown in Figure 9-12. The direction of displacement is toward the inlet sprue rather than away, as would be expected if this was due to the fluid drag or wire wash

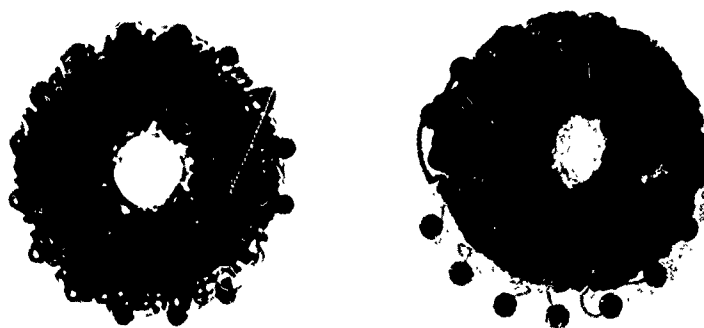


Figure 9-12. X-ray of toroidal coil before and after encapsulation by LIM process.

mentioned in 9.1.5.1. Since the resin is introduced at the rear of the mold (top of the part) it is possible that this motion is due to pressure caused by swirling of the resin as it flows into the mold. Further work needs to be done to determine the cause.

9.1.5.3 Conclusions

It is felt that while the described processes have shown excellent promise as a production method for encapsulating "high-rel" magnetic components, additional work is required before either represents a truly economically viable production method.

This would entail selection of a resin system with a much shorter cure time, process optimization to minimize cycle time, the selection of the appropriate auxilliary equipment (such as automatic metering/mixing, vacuum oven, post curing ovens, etc.); and in particular, molds specifically designed for this type of operation. Some requirements of these molds are outlined below.

1. Multi-cavity
2. Employ cavity inserts for flexibility
3. Usable with automatic mixing/metering equipment
4. Automatic knockout system
5. Cored for rapid heating and cooling
6. High and low pressure seals
7. Minimum seal area for configuration
8. Designed for fast curing materials

One further point worthy of note is the effect that implementation of this process would have on the designers of magnetic components. To be truly effective, the capital equipment costs would need to be spread over the manufacture of many component types since most high-rel magnetics are produced in relatively low quantities. This would mean that magnetics designers would need to consider standardization of both sizes and configurations and that manufacturers would need to control their winding processes more effectively in order to minimize component size variation.

9.2 EVALUATION OF AUTOMATIC MIXING AND METERING EQUIPMENT

One of the limitations encountered in the implementation of a continuous process is the mixing operation required for the encapsulent materials. Usually this is a batch process where the materials are measured out into a container, then mixed, either by hand or with power equipment, and poured into the mold within the allowable pot life specification. Also, during part or all of the mixing process, vacuum degassing is used to remove entrapped air.

An alternate approach to the mixing and degassing, just prior to use, is the freezing of the mixed and degassed material for long term storage, far beyond its pot life. This again is usually limited to batch operations in small quantities and is expensive in comparison with other methods, because of the cold storage required. However, there are distinct advantages for frozen premix, so it was evaluated and reported as a part of this subtask.

Automatic mixing and metering equipment for the plastics molding industries come in all flow ranges, ranging from gallons per minute to a fraction of a gallon per hour.

As a parallel effort, an in-house study was made of various mixing methods for Epon 825/HV to compare their adequacy and completeness of mix. Mixing techniques included hand mixing, "paint shaker" mixing, and rotary mixing.

The MM&T survey of metering and mixing devices was done from two standpoints: a survey of the encapsulation needs of a small, medium and large high reliability magnetics vendor on the one hand and a survey of commercially available metering and mixing equipment on the other.

9.2.1 Analysis of Resin Usage

The first step in the purchase of an automatic metering and mixing system is an analysis of the present resin usage. Many of the equipment vendors give their prospective customers a self-survey form, which Figure 9-13 is typical. This particular company makes equipment for a wide range of applications so that several lines are needed to identify the use, and others apply only for special uses. Some of the questions are obvious, while others may not be, so they will be commented on in detail, by reference numbers.

Plural Component Material Test Request

			TEST NO.
			DATE
END USER	CONTACT	ADDRESS	PHONE
DISTRICT MANAGER	ADDRESS	REGION	PHONE
DISTRIBUTOR	CONTACT	ADDRESS	PHONE

I. APPLICATION INFORMATION

- (1) ☐ AUTOMATIC ☐ ELECTRIC ☐ PNEUMATIC ☐ EXPLOSION PROOF ☐ HYDRAULIC ☐
☐ MANUAL ☐ TOTAL ☐ SEMI-AUTOMATIC ☐
(2) ☐ CIRCULATING ☐ MAINTAIN TEMP. ☐ HOLD SUSPENSION ☐
☐ DEAD END
☐ AIR SPRAY
(3) ☐ AIRLESS SPRAY
☐ EXTRUSION
(4) ☐ TRANSFER
(5) ☐ METERING
(6) ☐ HEATED
(7) ☐ CURING
- MIL THICKNESS W/O SAG: WET _____ DRY _____
- MIL THICKNESS W/O SAG: WET _____ DRY _____
- BEAD SIZE _____ RIBBON SIZE _____ FT PER MINUTE _____
- VOLUME REQD. _____ DISTANCE _____
- SHOT SIZE _____ TIME _____
- TEMPERATURE (A) _____ °F (B) _____ °F
- AIR DRY ☐ BAKE ☐ _____ °F
- (8) SUBSTRATE _____ AVAILABLE PLANT AIR PSI _____ CFM _____
(9) ☐ POUR ☐ SHOT SIZE _____ TIME _____
☐ FROTH ☐ SHOT SIZE _____ TIME _____

II. MATERIAL INFORMATION		BASE (A)	CATALYST (B)
(10)	MANUFACTURER		
	MATERIAL NAME		
	MATERIAL NUMBER		
	MATERIAL CONTAINER SIZE (FOR TEST)		
(11)	MATERIAL CONTAINER SIZE (FOR ACT. APPLIC.)		
	RATIO BY VOLUME		
	RATIO BY WEIGHT		
	RATIO TOLERANCE		
(12)	SOLVENT FOR THINNING		
	SOLVENT FOR CLEAN-UP		
	IS MATERIAL CORROSIVE?	<input type="checkbox"/> YES <input type="checkbox"/> NO	<input type="checkbox"/> YES <input type="checkbox"/> NO
(13)	IS MATERIAL ABRASIVE?	<input type="checkbox"/> YES <input type="checkbox"/> NO	<input type="checkbox"/> YES <input type="checkbox"/> NO
	VISCOSITY CPS	_____ 72° F _____ °F	_____ 72° F _____ °F
(14)	POT LIFE	SEC. _____ MIN. _____ HRS. _____ °F	SEC. _____ MIN. _____ HRS. _____ °F
(15)	SOLIDS BY VOL. (PERCENT)		
	TOXIC MATERIAL PRESENT	<input type="checkbox"/> YES <input type="checkbox"/> NO	<input type="checkbox"/> YES <input type="checkbox"/> NO
(16)	IS MATERIAL DANGEROUS?	<input type="checkbox"/> YES <input type="checkbox"/> NO	<input type="checkbox"/> YES <input type="checkbox"/> NO
	MATERIAL DISPOSITION	<input type="checkbox"/> SCRAP <input type="checkbox"/> HOLD <input type="checkbox"/> RETURN	<input type="checkbox"/> SCRAP <input type="checkbox"/> HOLD <input type="checkbox"/> RETURN

III TEST OBJECTIVE _____

- * PROBABILITY OF USER BUYING A SYSTEM? _____
* MAX. PRICE USER WILL PAY FOR SYSTEM? _____
* PROBABILITY OF USER BUYING THIS SYSTEM FOR NOTED PRICE? _____
* ANY COMPETITION? _____ WHO? _____

BEFORE EACH TEST WILL BE SCHEDULED, THE FOLLOWING MUST BE SUBMITTED:

1. SUFFICIENT SUPPLY OF MATERIAL (SENT FREIGHT PREPAID) TO FLUID SYSTEMS LAB, ATTENTION LAB SUPERVISOR
2. A MATERIAL MANUFACTURER'S DATA SHEET.
3. THIS FORM WITH ALL QUESTIONS ANSWERED.
4. DATA FOR MATERIAL DISPOSAL.

Form No. 316-533 Rev. 5-78 Printed in U.S.A.

Figure 9-13. Typical metering-mixing equipment survey form (Sheet 1 of 2)

HYDRA-CAT TEST REPORT

TEST NO.

DATE

I. CONCLUSIONS

II. RECOMMENDED EQUIPMENT

III. TEST RESULTS

MIN. AIR SUPPLY PSI	AIR CONSUMPTION CFM	MANIFOLDS. BASE PSI	CATALYST PSI
---------------------------------------------------------------------------------------------------------------	---------------------------------------------------------------------------------------------------------------	---------------------------------------------------------------------------------------------------------------	--------------------------------------------------------------------------------------------------------

TIP OR NOZZLE.

AIR SPRAY FLUID TIP AIR CAP CFM PSI MILS / PASS

AIRLESS SPRAY TIP PSI MIN. FLUID ATOMIZING PRESSURE MILS / PASS

EXTRUSION NOZZLE SIZE BEAD SIZE FT. / MINUTE

TRANSFER HOSE SIZE LENGTH GPM FLOW RATE

IV. TEST EQUIPMENT SET-UP

<input type="checkbox"/> FIXED RATIO BASE (A) → CATALYST (B) →	<input type="checkbox"/> VARIABLE RATIO: AIR MOTOR MOUNTING PROP. CYLINDER HOSE TO MIXER? DIA. LENGTH PROP. CYLINDER HOSE TO MIXER? DIA. LENGTH	<input type="checkbox"/> HYD. SOL. PUMP HOSE (SIZE - LG.) GUN: <input type="checkbox"/> MANUAL <input type="checkbox"/> AUTO MIXER: <input type="checkbox"/> POWER <input type="checkbox"/> STATIC. MIX MANIFOLD HEATERS REGULATORS
-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

☐ IMMERSED ☐ GRAVITY FEED ☐ PRESSURE FEED
☐ FEED PUMPS A B ☐ PRESSURE POT ☐ RAM INDUCTION
 OPERATING PRESSURE A B
 OTHER EQUIPMENT

V. COMMENTS:

THIS INFORMATION WAS DEVELOPED UNDER LABORATORY CONDITIONS WHICH MAY VARY WITH ACTUAL FIELD APPLICATIONS.

DEMONSTRATION ATTENDED BY
 TEST ENGINEER: SOLVENT: TIME: APPROVAL:
 COPIES SENT TO:

Figure 9-13. Typical metering-mixing equipment survey form (Sheet 2 of 2)

(1) The type of power available for the pumps-electrical, pneumatic, hydraulic, or special explosion proof electric motors is requested. (2) Refers to need for storing the resins at a certain temperature. The resins fillers sometimes come out of suspension; for this reason, the manufacturer is asking if resin stirring is needed during storage. (3) Is concerned with the mil thickness without sag, bead size and feet of ribbon/min for adhesive or spray applications. (4) Volume required and distance of the applicator from the pump refers to remote applicators with a central pump and storage applications. (5) Shot size and delay time between shots intimates that automatic metering and mixing equipment is better for repeated usage than for occasional use. The delay per shot can be varied over a range to allow the parts to be rapidly and repeatedly filled with resin as they move under the applicator. (6) The temperature of the A&B material refers to the required temperature of the resins. (7) Air dry or baked material refers to the curing method to be used. (8) The type of substrate question deals with adhesives and spray applications. The available air question asks what utilities especially air is available. (9) In the case of foams, the vendor wants to know if the uncured material is poured before frothing or after frothing.

(10) The material characteristics are listed; the manufacturer's name and resin's number, container size and mix ratio by weight and volume give basic material properties and give the mixer vendor's engineers a reference for further resin parameter data if necessary. (11) The container size used presently gives a rough estimate of the volume used. (12) Of real interest to the manufacturing engineer responsible for the equipment maintenance is the identification of an effective cleaning solvent and a thinning solvent. (13) The mixer and metering equipment design are affected by the corrosive nature of the resins and the abrasive nature of the fillers.

(14) The viscosity of the mixed resin and pot life at 72°F is to determine what type of material shut off is required at the dispenser and secondly, what kind of timer is needed to control the resin flush cycle. (15) The solids by volume percent relates to how much resin thinner (diluent) is in the material.

(16) The following questions concerning toxic material present, material dangers, disposition of mixed resin test samples, relate to the

actual prototype test this particular company does using the subject encapsulation material.

The reverse side of the survey form is the test report on work performed by the equipment vendor on the encapsulant materials described previously.

9.2.2 Survey of Equipment Vendors

The self-survey provides the information needed to ascertain the true needs. A survey of the available equipment vendors was carried out using lists from Modern Plastics Magazine, Reference 14.4; Electronic Design's Gold Book; and the Thomas Register, Reference 14.6. Each vendor listed was telephoned and a catalog of available equipment was requested. In several cases, the vendors made equipment to handle solid pellets or fluidized bed particles. As the survey was to find metering, mixing and dispensing equipment for the resins selected in the basic phase, these brochures were catalogued, but vendor representative visits were not suggested. There was a wide range of volume levels of automation and ultimately, cost. The equipment ranged from two plastic jugs with a calibrated plunger for the "A" and the "B" material to a fully automated, fully integrated meter, mix, storage and vacuum dispensing system. In between these extremes were several metering and mixing machines consisting of two cylinders and a common dispensing lever actuating valves and the mixer.

Certain vendors provided only part of a complete system; other vendors provided complete systems as a package. No general recommendation can be given as to one vendor over the others. Each customer needs to review its requirements and obtain equipment to meet the needs. In general, metering equipment allows a cleaner work space than a hand mix operation with the attendant throw away cartons. However, automatic equipment operated best where the machine is run continuously during the shift rather than sporadically. The reasons for these generalizations are these: hand mix operations require mixing cartons which may be difficult to dispose of properly; each time the mixing equipment is stopped for more than two-thirds of the resin pot life, the mixer must be purged of mixed resin and catalyst in order to avoid freezing the mixer with cured resin.

9.3 MIXING STUDY

Production of high reliability encapsulated electromagnetic devices, requires that an optimum encapsulant be used and that it be processed properly. Consequently, a program to improve encapsulation processability as a part of the overall MM&T program was established.

This section provides some information on an encapsulant (Epon 825-HV hardener system) and its processability, based on the investigation as follows:

1. Evaluate the techniques for homogeneous mixing of the resin parts
2. Determine the properties of the encapsulant prepared by different mixing techniques
3. Develop a reliable method to determine the resin homogeneity
4. Determine the properties of the encapsulant (Epon 825-HV hardener resin system) when cured below the recommended curing schedule per a control material specification. (It was reported that, in the past, the subject resin system has been used to encapsulate devices with a temperature limitation of 70°C.)

9.3.1 Test Procedures and Results

9.3.1.1 Test Materials

Epon 825, meeting the requirements of HMS 16-1576 Type I, and HV hardener were used throughout this evaluation.

9.3.1.2 Test Sample Processing

All epoxy resin samples were processed in accordance with HP 16-92, Type I, Class 1, except that 1) resin mixing was accomplished by three different techniques, and 2) specimen curing was done at 71°C (160°F) for sixteen (16) hours in air.

Mixing techniques employed in this evaluation were:

- Hand mixing
- Paint shaker mixing
- Rotary mixing.

9.3.1.3 Evaluation

The following determinations and tests were performed on the samples of mixed resin before curing and on "cured" specimens.

Samples of Mixed Resin before Curing (Part I)

- Homogeneity of mixed resin by FT-IR technique.

"Cured" Test Specimens (Part II)

- Specific gravity
- Hardness (Shore D)
- Degradation temperature
- Glass transition temperature (T_g)
- Coefficient of thermal expansion
- Moisture absorption
- Shrinkage

9.3.1.4 Mixed Resin Systems Before Curing (Part I): Determination of Mixed Resin Homogeneity by Infrared Analysis Technique

An attempt was made to determine how well the resin system mixing can be achieved by three different methods described in 9.3.1.2 above. In this study, a Fourier Transform Infrared (FT-IR) spectrometer was employed to determine the functional group absorbances of the resin parts and to determine semi-quantitatively the amount of Epon 825 and HV hardener present in the mixed epoxy resin systems.

1. Standardization of Epoxy Resin System

a. Identification of Optimum Functional Group Absorbances

After a number of evaluations and analyses, it was determined that the absorbance bands at 3370 cm^{-1} (primary amine stretching) and 1035 cm^{-1} (carbon-oxygen stretching) appeared reliable.

Accordingly, the subject absorbance bands were used throughout this evaluation to determine the Epon 825 and HV hardener ratios in the mixed resins.

b. Stability (Pot Life) Determination

A thin film of a thoroughly blended Epon 825-HV hardener (approximately 18 percent by weight HV hardener) was cast on a sodium chloride crystal for FT-IR analysis. The crystal was then exposed to air at ambient temperature and analyzed periodically with a FT-IR spectrometer.

Results

No noticeable or significant changes at the 3370 cm^{-1} and 1035 cm^{-1} regions of the spectrum were observed even after 60 minutes at ambient temperature.

c. Reproducibility Determination

The epoxy resin samples with approximately 20 percent by weight of HV hardener were thoroughly blended, cast as thin films on five sodium chloride crystals, and analyzed within a half hour using a FT-IR spectrometer. The absorbance peaks 3370 cm^{-1} and 1035 cm^{-1} were measured from the spectra, and the standard deviation of the absorbance peak ratios was determined.

Results

With the exception of one sample, the absorbance peak ratios of all samples were very close. The standard deviation of all the values was approximately 7 percent; but approximately one percent if that one value was excluded (see Table 9-1).

d. Standard Curve Determination

Various formulations of the Epon 825-HV hardener epoxy resin system were prepared to establish a standard curve or calibration curve.

One set of the resins was cast as thin films on sodium chloride (NaCl) crystals, and another set was introduced into sodium chloride cells with a known sample thickness (0.038 mm).

Assuming the curve (absorbance peak ratio versus concentration) is linear, the linear best fit was determined.

Results

As shown in Table 9-2, both curves show very small deviations. Accordingly, all absorbance peak ratios were used to determine a standard curve line of fitness (shown in Figure 9-14).

TABLE 9-1. REPRODUCIBILITY DETERMINATION: FT-IR
SEMI-QUANTITATIVE ANALYSIS

Sample	Absorbance Peak		Absorbance Peak Ratio (% HV Hardener)	Standard Deviation (% Deviation) (Note 2)
	3370 cm^{-1}	1035 cm^{-1}		
1	2.48×10^{-2}	1.85×10^{-1}	1.34×10^{-1} (22)	$\sigma = 0.014$ $\bar{x} = 1.34 \times 10^{-1}$ } $\sigma = 0.0099$ (1 percent) } $\bar{x} = 1.38 \times 10^{-1}$ (7 percent)
2	2.76×10^{-2}	2.09×10^{-1}	1.32×10^{-1} (21)	
3	3.35×10^{-2}	2.48×10^{-1}	1.35×10^{-1} (22)	
4	3.25×10^{-2}	2.40×10^{-1}	1.35×10^{-1} (22)	
5 (Note 1)	4.74×10^{-2}	3.04×10^{-1}	1.56×10^{-1} (26)	
Notes: 1. Probably some errors during sample number 5 preparation.				
2. σ = standard deviation				
\bar{x} = mean value				

TABLE 9-2. STANDARD CURVE DETERMINATION

Percent HV Hardener	Ratio of Absorbance Peaks (Note 1)	
	Using NaCl Crystal (Note 2)	Using NaCl Cell (Note 3)
5	0.44×10^{-1}	0.44×10^{-1}
10	0.58×10^{-1}	0.66×10^{-1}
	0.76×10^{-1}	
15	1.04×10^{-1}	0.91×10^{-1}
20	1.25×10^{-1}	1.31×10^{-1}
25		1.52×10^{-1}
30	1.8×10^{-1}	
Best Linear (Note 4)	$m = 0.00549$ $b = 0.0162$	$m = 0.00562$ $b = 0.0125$
	Combination of both methods: $m = 0.00557$ $b = 0.0138$	

(Continued next page)

(Table 9-2, concluded)

- NOTES: 1. Ratio of absorbance peaks at 3370 cm^{-1} and 1035 cm^{-1}
2. IR samples were prepared by casting thin films on NaCl crystal surfaces
3. IR samples were prepared in NaCl cells of known thickness
4. $y = mx + b$, where y = Absorbance Ratio
 x = Percent HV Hardener
 m = Slope
 b = y intercept

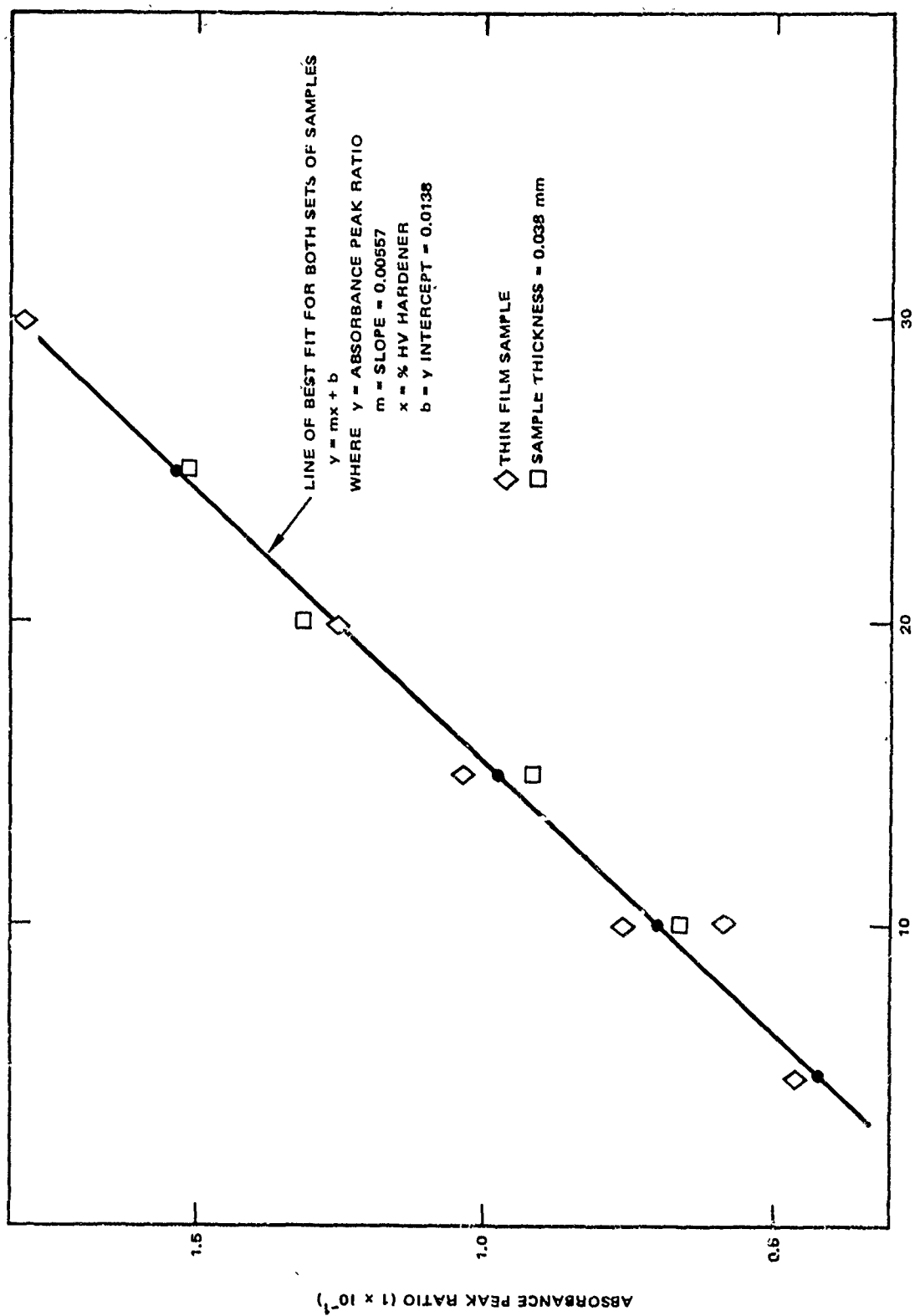


Figure 9-14. Absorbance peak ratios (3370 cm^{-1} for HV hardener and 1035 cm^{-1} for EPON 825) vs HV hardener concentration: standard curve.

2. FT-IR Analysis of Resin Samples: Mixing Evaluation

a. Sampling

Epon 825-HV hardener systems were prepared in canisters using the three different mixing techniques listed in Section 9.3.1.2.

Using a pipet, a small amount of resin was carefully sampled from various parts of the canister containing freshly mixed resin. The sample was then cast as a thin film on a sodium chloride crystal.

The sampled areas were:

- Near the top
- Near the top adjacent to the canister's wall
- Near the center
- Near the bottom
- Near the bottom adjacent to the canister's wall.

b. FT-IR Analysis

The samples prepared as described above were analyzed within thirty minutes after mixing with a FT-IR spectrometer.

Results

The ratios of absorbance band peaks at 3370 cm^{-1} and 1035 cm^{-1} for each sample were determined from the spectra and are shown in Table 9-3.

This evaluation shows that the rotary mixing method appears most reliable; the paint shaker method appears least reliable.

9.3.1.5 "Cured" Epoxy Test Specimens: Evaluations (Part II)

The test specimens were prepared from the epoxy resins mixed in accordance with the three different methods (9.3.1.2). Limited evaluation was conducted on the specimens to determine if there was any significant difference in properties due to different mixing methods.

1. Specific Gravity

Specific gravity of the specimens was determined at ambient temperature (22°C) in accordance with Fed. Std. 406-5011 water displacement method.

TABLE 9-3. ABSORBANCE PEAK RATIOS: MIXING METHOD EVALUATION

Sampling Areas	Ratio of Absorbance Peaks at 3370 cm ⁻¹ and 1035 cm ⁻¹		
	Hand Mixing (% HV Hardener)	Paint Shaker Mixing (% HV Hardener)	Rotary Mixing (% HV Hardener)
Near Top	0.92 x 10 ⁻¹ (14%)	1.04 x 10 ⁻¹ (16%)	1.32 x 10 ⁻¹ (21%)
Near Top Adjacent To Wall	1.2 x 10 ⁻¹ (19%)	1.47 x 10 ⁻¹ (24%)	1.16 x 10 ⁻¹ (19%)
Near Ce. ter	0.82 x 10 ⁻¹ (12%)	1.05 x 10 ⁻¹ (16%)	1.28 x 10 ⁻¹ (20%)
Near Bottom	1.07 x 10 ⁻¹ (17%)	1.13 x 10 ⁻¹ (18%)	1.38 x 10 ⁻¹ (22%)
Near Bottom Adjacent To Wall	1.02 x 10 ⁻¹ (16%)	1.37 x 10 ⁻¹ (22%)	1.24 x 10 ⁻¹ (20%)
Standard Deviation (Note 1)	σ = 0.0144 \bar{x} = 0.1007 (14% devia- tion)	σ = 0.0196 \bar{x} = 0.1212 (16% devia- tion)	σ = 0.0083 \bar{x} = 0.1276 (7% devia- tion)
Note 1. σ = standard deviation \bar{x} = mean values			

Results

As shown in Table 9-4, the specific gravity of all test specimens was 1.18. The specification requirement of HMS 16-1576, Type 1 is 1.2.

2. Hardness

Hardness of the test specimens was determined per Fed. Std. 406-1083 at ambient temperature (22°C).

Results

All test specimens had hardness values of about 70 Shore D; specification HMS 16-1576, Type 1 calls for 80 Shore D or above. Consequently, there is doubt that the test specimens were fully cured.

3. Degradation Temperature

The degradation temperature of the test specimens was determined by Thermogravimetric Analysis (TMA) and Differential Scanning Calorimetric (DSC) techniques using a Du Pont Thermal Analyzer.

Results

No significant differences among test specimens were observed: all specimens appeared to decompose readily at approximately 300°C (see Table 9-4 and Figures 9-15 to 9-25).

4. Glass Transition Temperature (T_g)

The glass transition temperature of the test specimens was determined by TMA and DSC techniques using the Thermal Analyzer.

To determine the cure stage of the test specimens, one of the specimens from the hand-mixed batch was heated up to 175°C at a 10°C/minute heating rate, cooled to room temperature, and then heated again, this time up to the decomposition temperature, at the same heating rate.

Results

The glass transition temperature of all test specimens appeared to be near 70°C with some endothermic reactions (melting). However, the glass transition temperature was considerably higher (near 100°C) for the test specimen exposed in the heat cycle to 175°C. This indicates that the test specimens were not fully cured (refer to Table 9-4 and Figures 9-15 to 9-25).

TABLE 9-4. EVALUATION OF EPOXY RESIN SPECIMENS
PREPARED FROM DIFFERENT MIXING METHODS

Evaluation	Epoxy Resin Mixing Methods		
	Hand Mixing	Paint Shaker Mixing	Rotary Mixing
1. Curing Schedule (Note 1)	16 Hours at 71°C	16 Hours at 71°C	16 Hours at 71°C
2. Specific Gravity (Note 2)	1.18	1.18	1.18
3. Hardness (Shore D) (Note 3)	73	73	70
4. Degradation Temperature (°C) (Note 4)	Near 300	Near 320	Near 290
5. Glass Transition Temperature (°C) (Note 4)	Near 70 to 75	Near 70	Near 65 to 75
6. Coefficient of Thermal Expansion (in/in/°C) (Note 4)	72 (25 to 50°C) 150 (100 to 300°C)	82 (25 to 50°C) 149 (100 to 300°C)	75 (25 to 50°C) 157 (100 to 290°C)
7. Moisture Absorption (%) (Note 5)	0.0815	0.0818	0.0810
8. Linear Shrinkage (%) (Note 6)	0.167	0.167	0.133
Notes: (1) Curing of test specimens was performed by Coating and Encapsulant Group (16-21-11) (2) Per Fed. Std. 406-5011 (3) Per Fed. Std. 406-1083 (4) Using Du Pont Thermal Analyzer (5) Per ASTM D570; Modified (6) Per ASTM D2566; Modified			

5. Coefficient of Thermal Expansion (CTE)

The CTE of the test specimens was determined from the TMA thermograms obtained in Sections 9.3.1.5c and 9.3.1.5d.

Results

For all test specimens, the CTE value below the glass transition temperature was near 70 to 80 in/in^{°C}; the CTE value above the T_g was near 150 in/in^{°C}. (Figures 9-17, 9-20, 9-23, 9-24).

All thermograms are in the Appendix.

6. Moisture Absorption

The moisture absorption of the test specimens was determined by 24 hours immersion at ambient temperature per ASTM D570. At least two specimens, 0.08 inch thick, prepared by each mixing technique were run.

Results

There was no difference in the moisture absorption as a result of the three mixing techniques, as indicated by average percentage weight increases of 0.0815, 0.0818, and 0.0810 for hand, paint shaker, and rotary mixing respectively.

7. Linear Shrinkage

The linear shrinkage of the test specimens was determined in a manner similar to ASTM D2566. The procedure used differs from the ASTM method in a few respects. The mold used was aluminum and three (3) inches long instead of stainless steel and 10 inches long, as specified in the ASTM method. Mold releasing agents were used instead of Teflon film to prevent adhesion of the resin material to the mold.

Results

All test specimens showed less than 0.2 percent shrinkage. No significant differences (shrinkage) were observed among the test specimens prepared by the three mixing techniques (see Table 9-4).

9.3.1.6 Conclusions

Using a Fourier Transform Infrared (FT-IR) spectrometer, a technique was developed to determine semi-quantitatively the amounts of the resin constituents in the mixed resin system before curing. In this method a

standard curve of the ratio of the absorbances at two frequencies against concentration of the components in the mixed resin system was obtained. After measurement of the absorbance peak ratio for the resin sample, the concentration of each resin component could be read directly from the standard curve. This technique was useful to determine the resin mixture homogeneity.

Within the scope of this investigation, the rotary mixing method appears most reliable in producing a homogeneous resin mixture; the paint shaker and hand mixing methods appear less reliable. However, other factors; such as degassing, duration of mixing, etc., must be precisely controlled to obtain completely reliable and reproducible information. Accordingly, it is recommended that the mixing techniques be further explored to measure their efficiency and to determine if they can be improved.

It is further concluded that there were no significant property differences between the cured materials prepared by different mixing methods (namely, hand, paint shaker, and rotary mixing).

The thermal analysis of the epoxy resin (Epon 825-HV hardener system) cured at 71°C for 16 hours indicates that the material exhibits an endothermic reaction with concurrent softening near 70°C.

9.3.2 Mixer and Frozen Premix Evaluation

This section covers the mixer evaluation and premix and frozen work performed for the MM&T Program. The mixing efficiency, processing parameters and functionality of a Hughes' designed vacuum rotary mixer were evaluated for capacitor encapsulation. The feasibility of premixing and freezing RTV 627, RTV 615, RTV 11, Epon 825/HV, Dow Corning Q3-6527, Schotchcast 255 and alumina filled Uralane 5753 resin systems was also determined.

TABLE 9-5. CTE DATA FROM FIGURE 9-17

EPON 825 with HV Hardener (HP 16-92, Type I, Class 1) (Hand Mixing) Coefficient of Thermal Expansion (CTE) by TMA <ul style="list-style-type: none"> • Sample Thickness = 0.1443 inch • Tg(?) = Near 70°C 			
°C	Δ°C	ΔL axis (in.)	CTE (1 × 10 ⁻⁶ in/in °C)
25 to 50	25	0.096	72 (below Tg)
100 to 150	50	0.478	178
150 to 200	50	0.317	118
200 to 200	50	0.363	136 (below Tg)
250 to 300	50	0.453	169
CTE Calculation $\frac{\Delta L \text{ axis (in.)} \times 0.008 \text{ mv/in.}}{\Delta^\circ\text{C} \times 0.1443 \text{ in.} \times 29.7 \text{ mv/in.}}$			

TABLE 9-6. CTE DATA FROM FIGURE 9-20

<p>Epon 825 with HV Hardener (HP 16-92, Type I, Class 1) (Paint Shaker Mixing)</p> <p>Coefficient of Thermal Expansion (CTE) by TMA</p> <ul style="list-style-type: none"> • Sample Thickness = 0.1428 inch • Tg(?) = Near 70°C 			
°C	Δ°C	ΔL axis (in.)	CTE (1 × 10 ⁻⁶ in/in °C)
25 to 50	25	0.108	82 (below Tg)
100 to 150	50	0.481	181
150 to 200	50	0.314	118 (above Tg)
200 to 250	50	0.356	134
250 to 300	50	0.433	
<p>CTE Calculation</p> <p>ΔL axis (in.) X 0.08 mv/in.</p> <p>Δ°C X 0.1428 in. X 29.7 mv/in.</p>			

TABLE 9-7. CTE DATA FROM FIGURE 9-23

Epon 825 with HV Hardener (HP 16-92, Type I, Class 1) (Rotary Mixing) Coefficient of Thermal Expansion (CTE) by TMA <ul style="list-style-type: none"> • Sample Thickness = 0.1485 inch. • $T_g(?) = \text{Near } 65^{\circ}\text{C}$ 			
$^{\circ}\text{C}$	$\Delta^{\circ}\text{C}$	ΔL axis (in.)	CTE (1×10^{-6} in/in $^{\circ}\text{C}$)
25 to 50	25	0.103	75 (below T_g)
100 to 150	50	0.518	188
150 to 200	50	0.288	105 (above T_g)
200 to 250	50	0.369	134
250 to 290	40	0.465	169
CTE Calculation ΔL axis (in.) $\times 0.08$ mv/in. $\Delta^{\circ}\text{C} \times 0.1485$ in. $\times 29.7$ mv/in.			

TABLE 9-8. CTE DATA FROM FIGURE 9-24

Epon 825 with HV Hardener
(HP 16-92, Type I, Class 1)
(Hand Mixing)

PROCEDURES:

- Heating to 175°C at 10°C/min. heating rate, cooling to ambient temperature, and then heating at the same heating rate to decomposition temperature (300°C)

SAMPLE THICKNESS: 0.1694 inch.

- Tg(?) for initial heating: near 60 to 75°C
- Tg for second heating: near 100 to 110°C

COEFFICIENT OF THERMAL EXPANSION (CTE) AT INITIAL HEATING:

°C	Δ °C	ΔL axis (in.)	CTE (1 x 10 ⁻⁶ in/in °C)
25 to 55	30	0.255	68 (below Tg)
110 to 135	25	0.637	211
135 to 175	40	0.718	143

COEFFICIENT OF THERMAL EXPANSION (CTE) AT SECOND HEATING:

°C	Δ °C	ΔL axis (in.)	CTE (1 x 10 ⁻⁶ in/in °C)
25 to 55	30	0.232	61 (below Tg)
110 to 135	25	0.620	197
135 to 175	40	0.912	156 (above Tg)
175 to 225	50	0.990	157
225 to 275	50	1.021	162

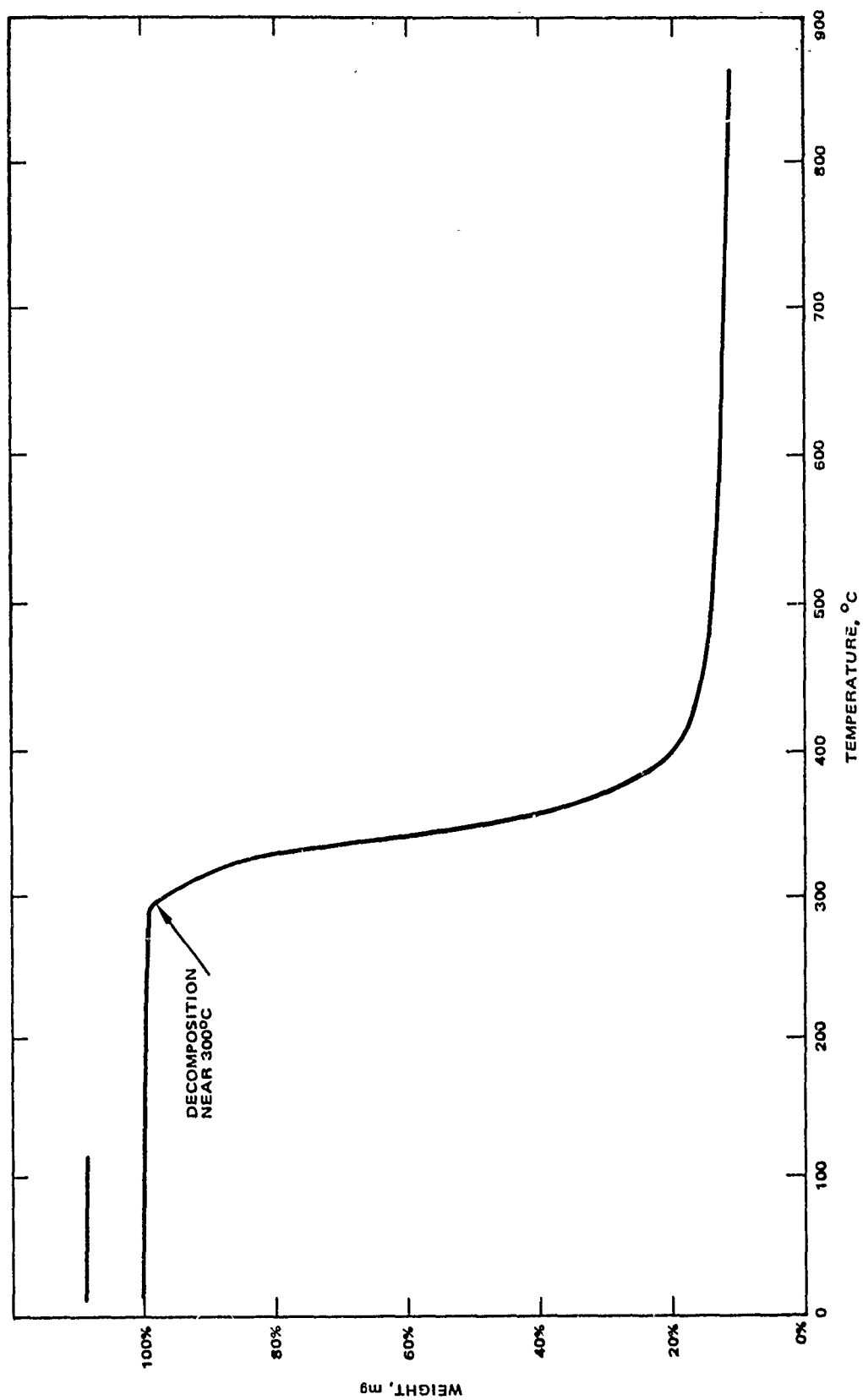


Figure 9-15. Thermogravimetric analysis, EPON 825/HV, hand mixing.

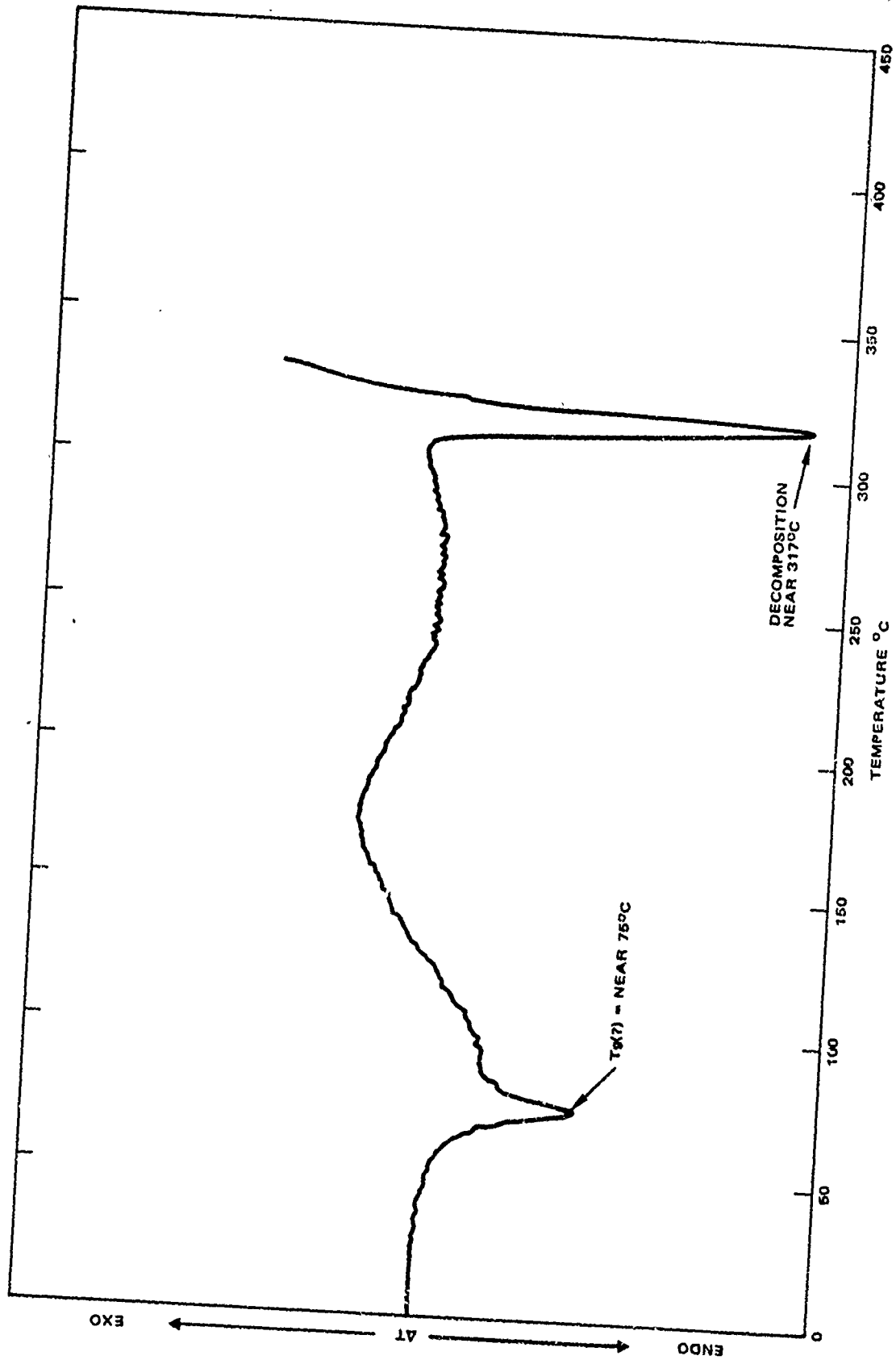


Figure 9-16. Differential scanning calorimetry EPON 825/HV, hand mixing.

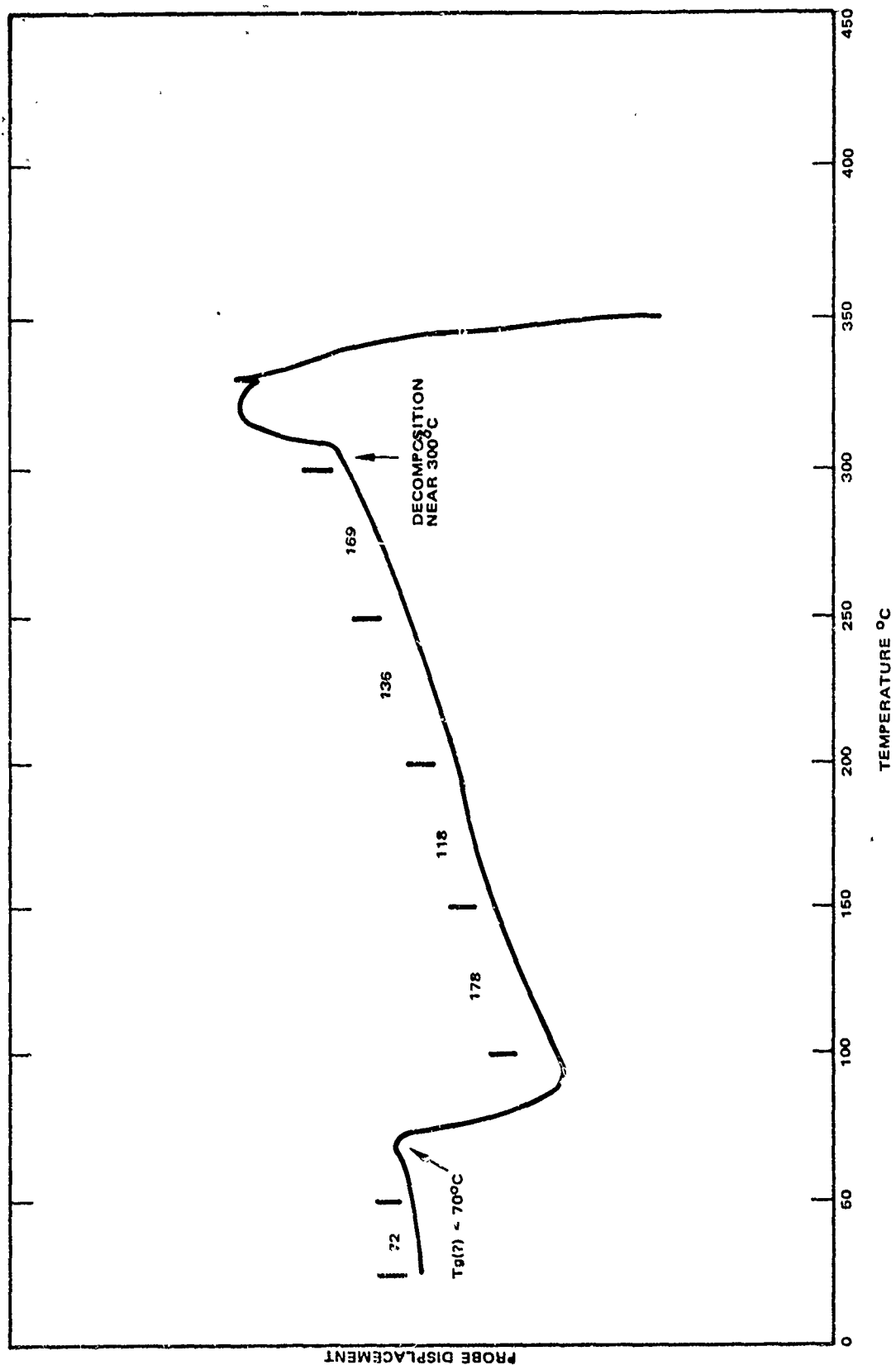


Figure 9-17. Thermomechanical analysis EPON 825. Hand mixing coefficient of thermal expansion unit = 1×10^{-6} in/in °C.

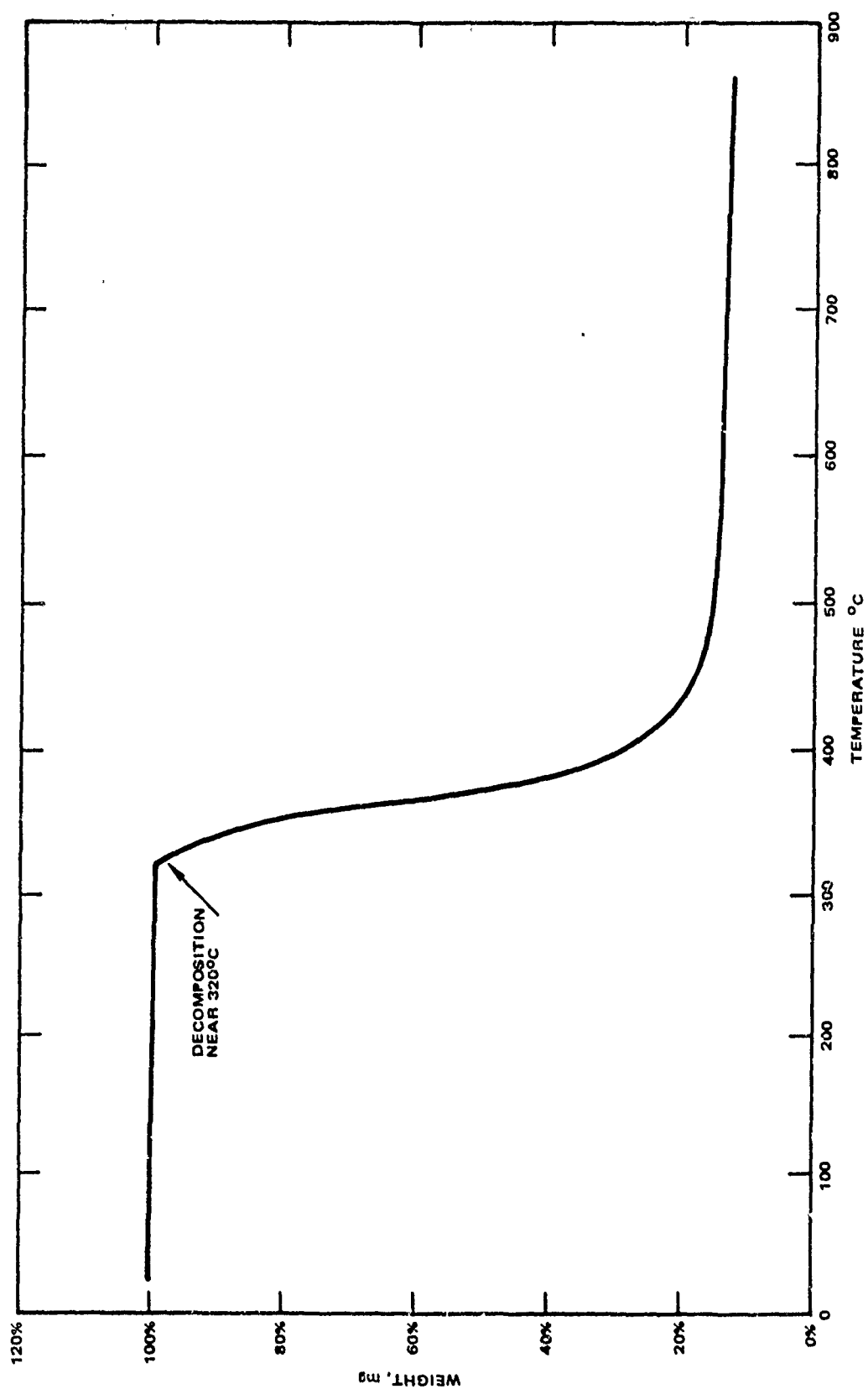


Figure 9-18. Thermogravimetric analysis, EPON 825/HV, point shaker mixing.

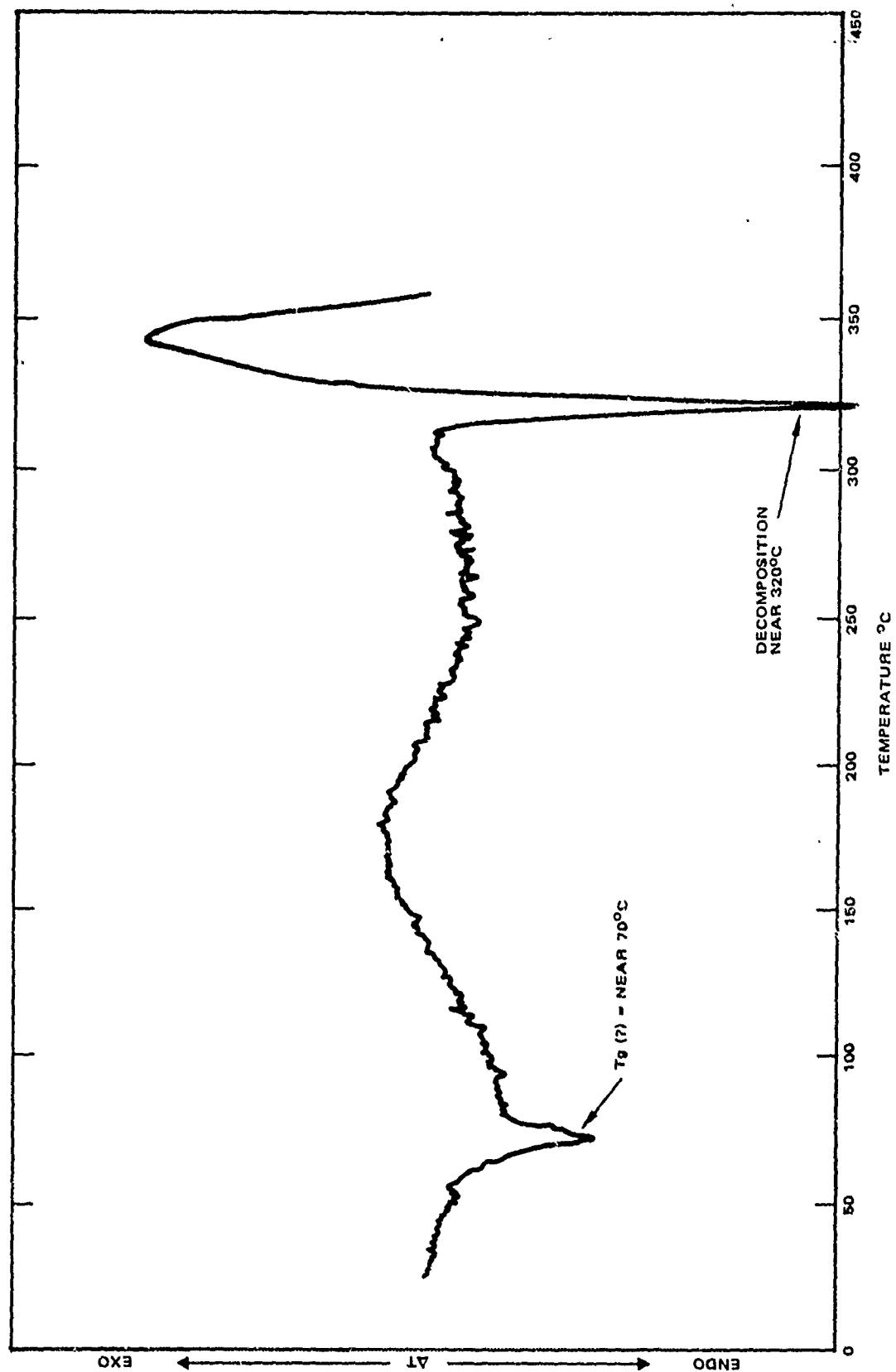


Figure 9-19. Differential scanning calorimetry, point shaker mixing.

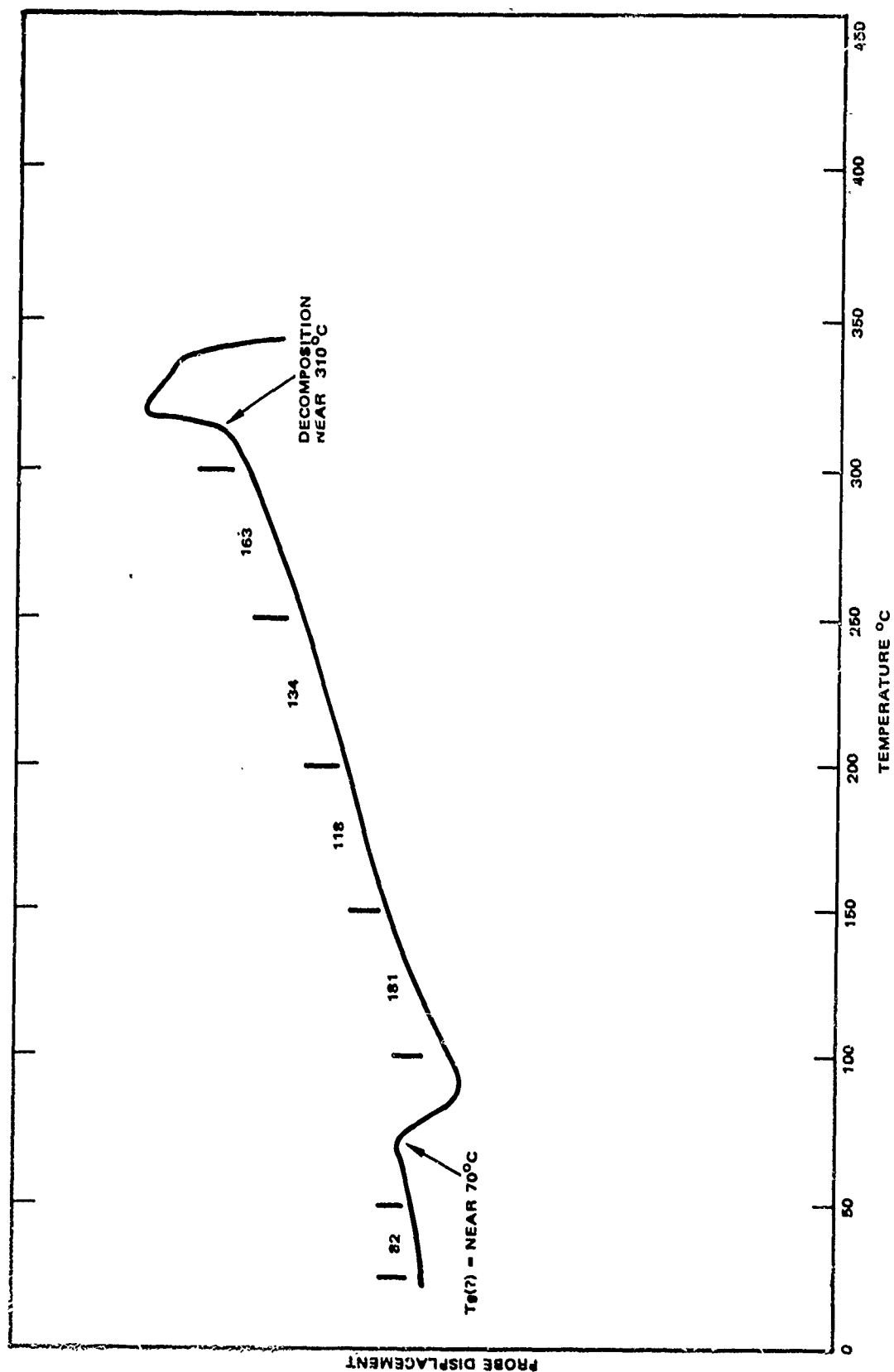


Figure 9-20. Thermomechanical analysis, EPON 825/HV, paint shaker mixing coefficient of thermal expansion unit = 1×10^{-5} in/in/°C.

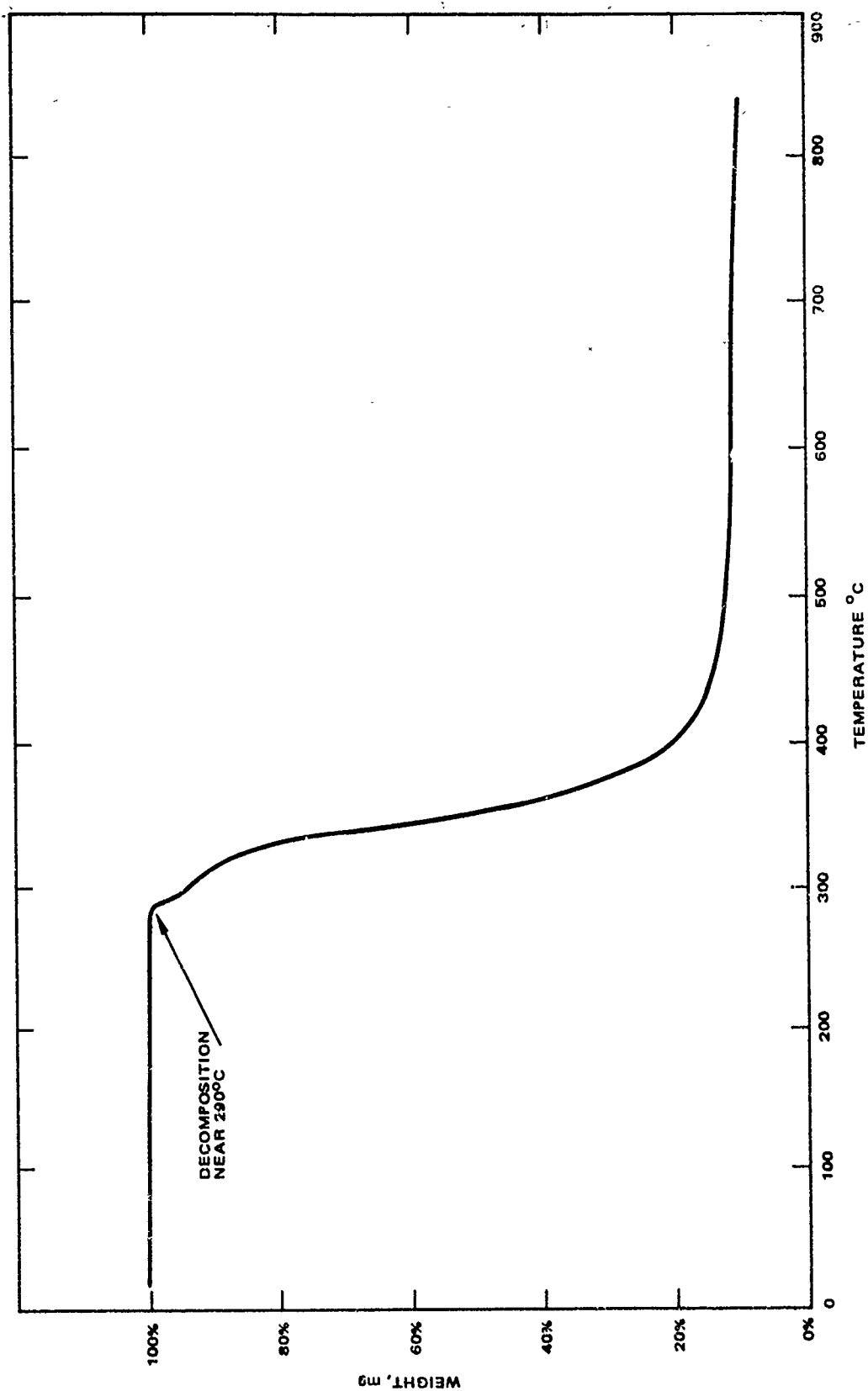


Figure 9-21. Thermogravimetric analysis, EPON 825/HV rotary mixing.

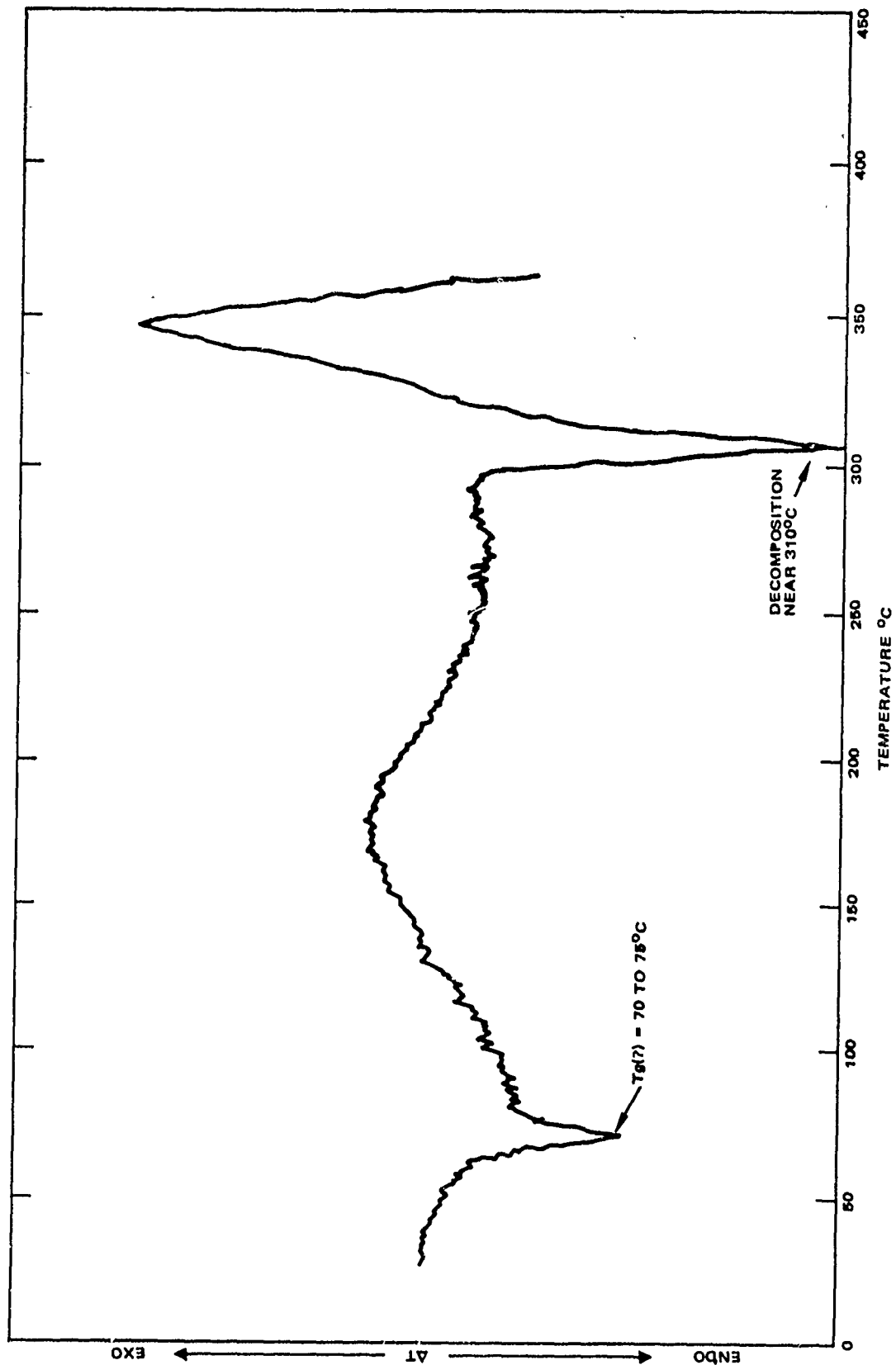


Figure 9-22. Differential scanning calorimetry, EPON 825/HV, rotary mixing.

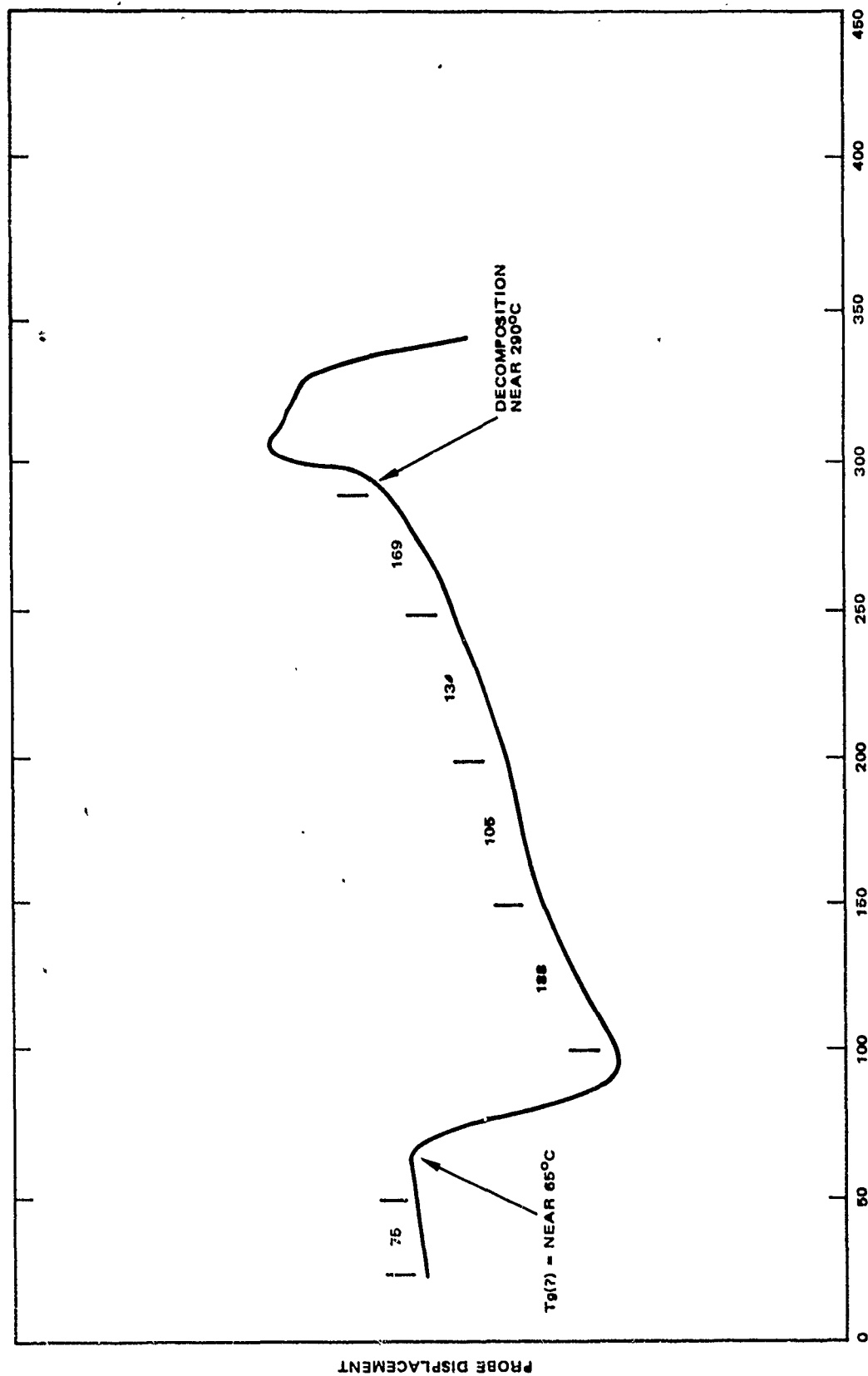


Figure 9-23. Thermomechanical analysis, EPON 825/HV, rotary mixing coefficient of thermal expansion (CTE) unit = 1×10^{-6} in/in/ $^\circ\text{C}$.

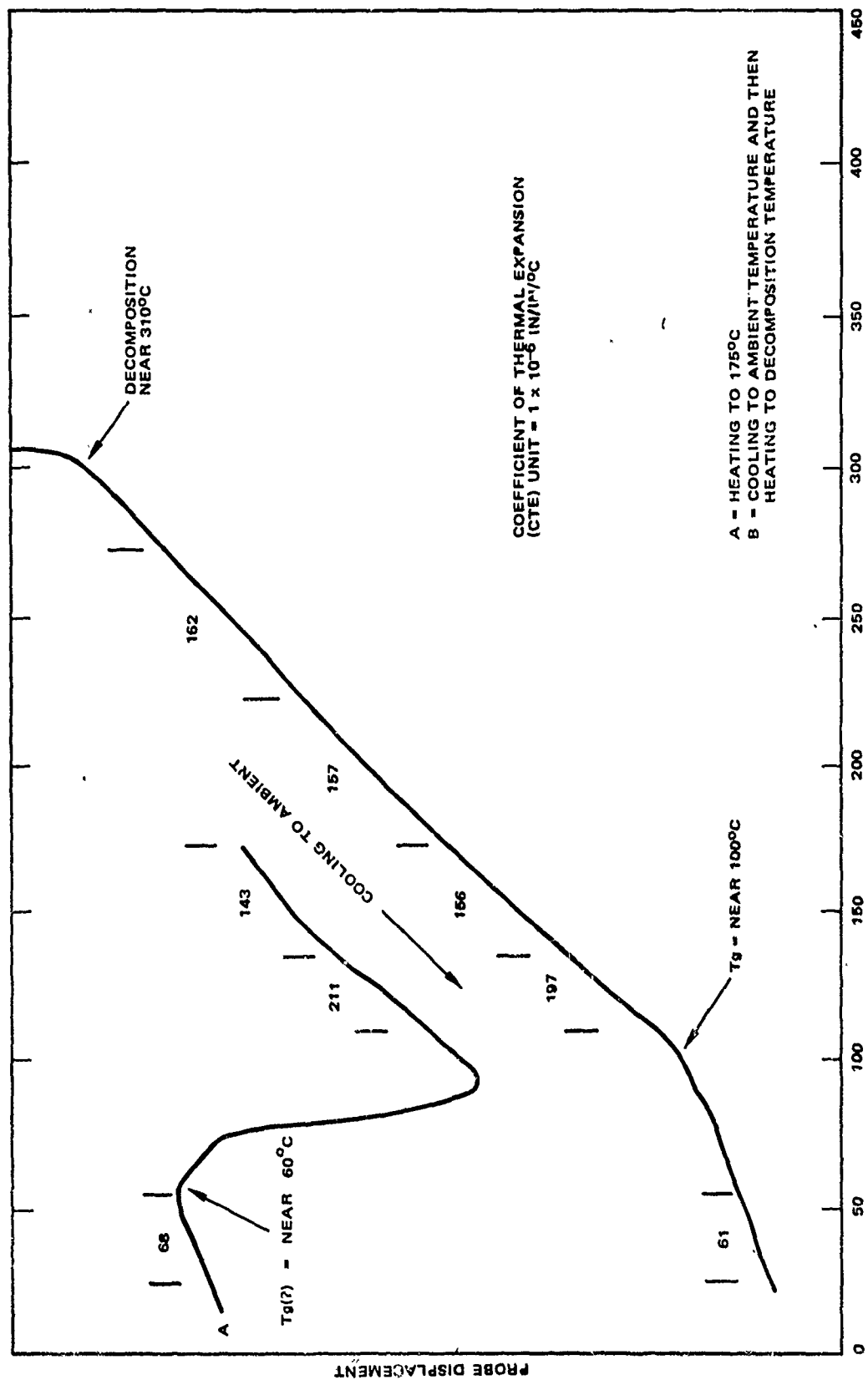


Figure 9-24. Thermomechanical analysis, EPON 825/HV hand mixing.

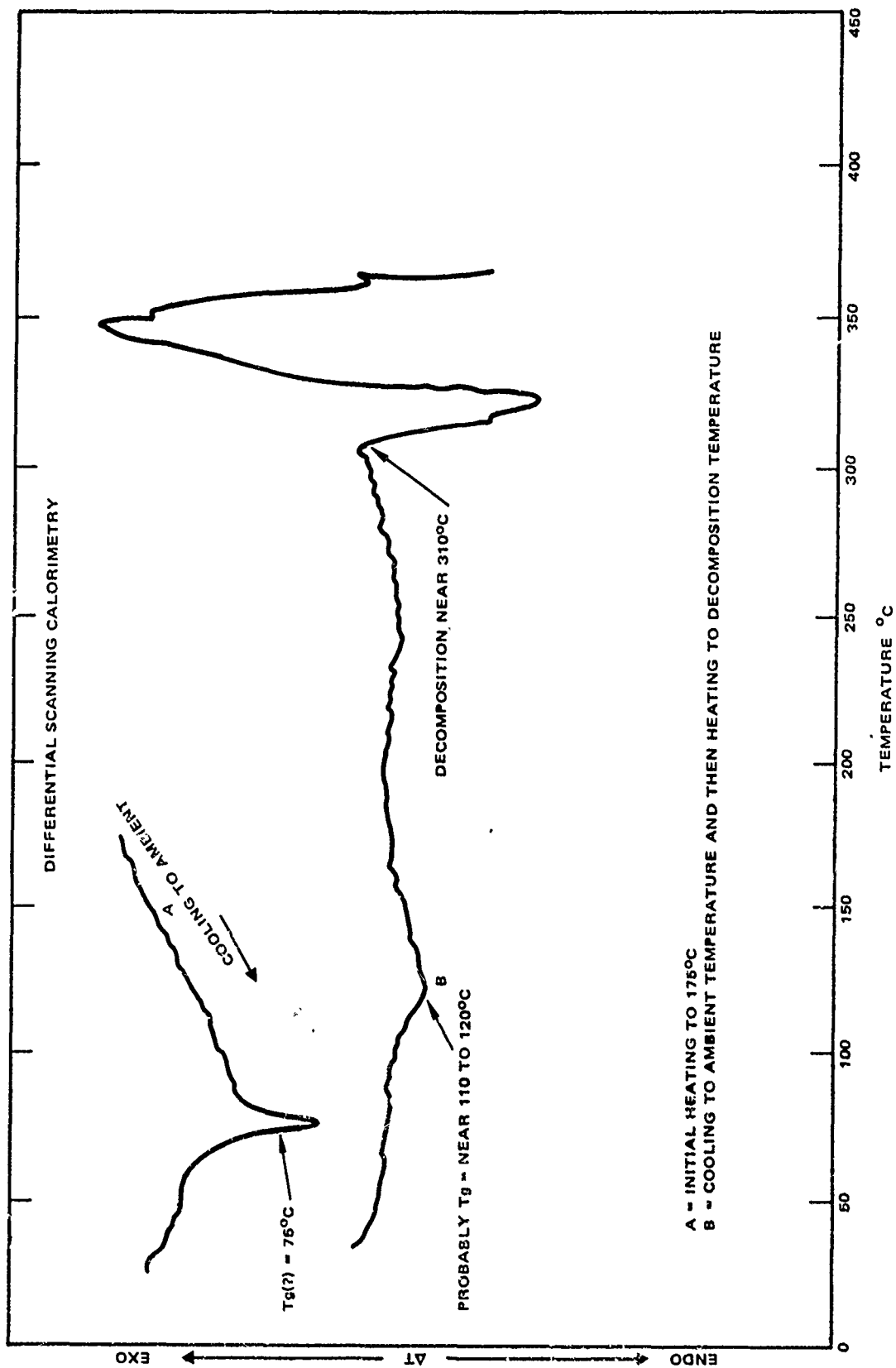


Figure 9-25. Differential scanning calorimetry.

9.3.2.1 Background

The flow chart in Figure 9-26 presents that part of the process sequence for embedding or encapsulating electronic assemblies. Steps 1 to 5 were used in the premix and frozen evaluation while steps 1, 3 and 4 were eliminated in the mixer study.

Embedding or encapsulating resins are those resins which can be converted from a liquid to a solid at room or slightly elevated temperatures, and at atmospheric or low molding pressures. The conversion process is known as curing or hardening. The low temperatures and pressures make these materials and processes attractive, especially for batch or short run production, when compared with molding. Pastic compounds utilized in molding require more expensive molds, high temperatures and pressures. Pressure is one of the most important aspects because processing costs are directly affected by the low cost tooling that can be used in low pressure processes.

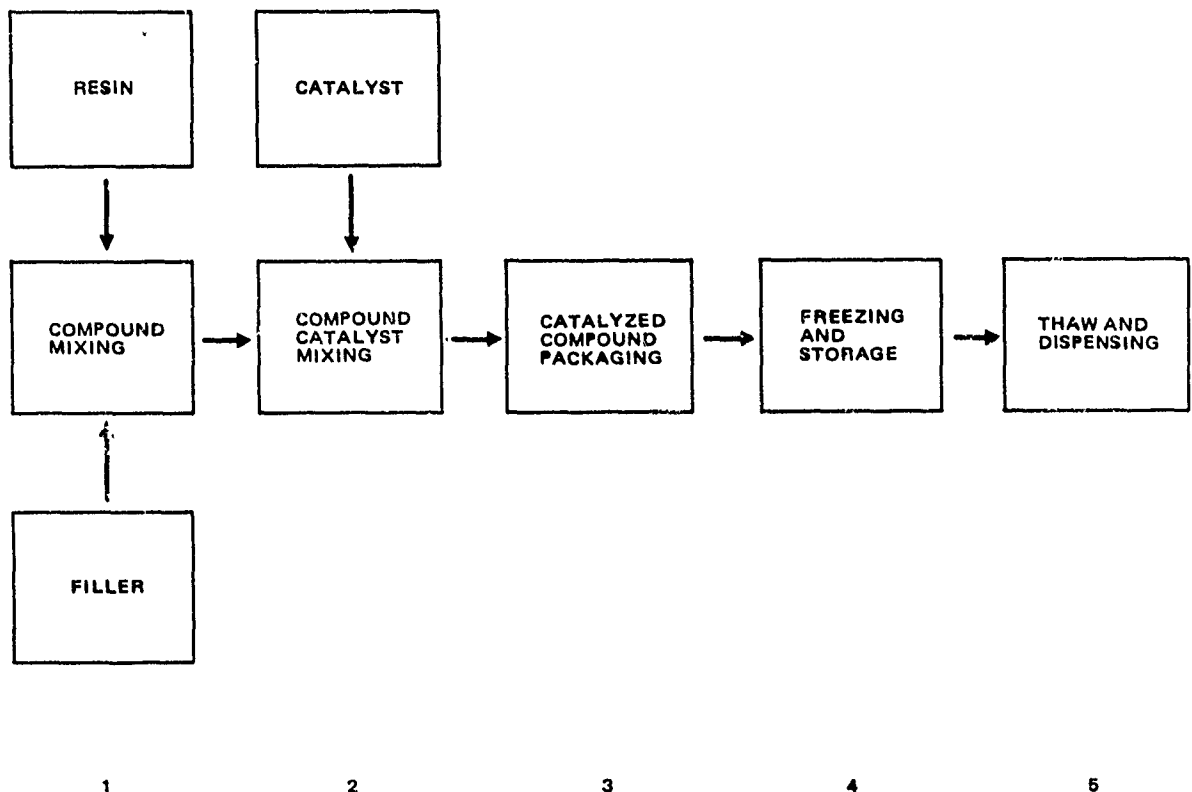


Figure 9-26. Process sequence evaluated in study of premix and frozen encapsulants.

The processing characteristics of encapsulating resins must be determined prior to the design or use of any metering and mixing equipment. Data such as viscosity, gel time and possible exotherm are necessary. The flow, a function of viscosity, is an important property because of the need for penetration of the resin at atmospheric or low pressures. When the viscosity of the resin is too high, the resin does not flow properly around inserts or components, creating internal cavities. A high viscosity material inhibits evacuation of entrapped air, again causing void formation.

The optimum viscosity for impregnation is 100 centipoise or less while viscosities for encapsulation in the range of 1000 to 5000 centipoise are satisfactory. Resin systems exceeding these values can still be used successfully if the application of heat can reduce the viscosity to an acceptable level without shortening the pot life to an unmanageable level.

Exotherm is the heat generated by the resin during the curing process. Most polymeric resins used for encapsulation have an exothermic reaction. The complete understanding of the exothermic characteristics will reduce the shortening of pot life and chances of generated heat affecting heat-sensitive components.

The use of premix and frozen materials eliminates the metering, mixing and degassing of resin systems, thereby reducing sources of error. Adequate incoming inspection can be performed on new shipments of premixed and frozen material to assure satisfactory performance of the resin system.

9.3.2.2 Preparation

The preparation of premix and frozen materials in this study was accomplished by use of the following equipment:

1. Air motor driven vacuum mixer
2. Electric heat sealer for sealing aluminized mylar bags
3. Packaging materials consisting of cartridges, plungers, and cap plugs.
4. Dry ice/methanol freezing bath.

The basic premixing and packaging procedure followed these steps:

1. Premix fillers into base resin under vacuum
2. Add catalyst and mix under vacuum
3. Fill resin formulation into cartridges
4. Place cartridge into an aluminized mylar bag
5. Evacuate the bag and heat seal.
6. Quick freeze the cartridge for 30 minutes by total immersion in the dry ice/methanol bath
7. Store at -65°F (-54°C) till required for use.

A specially designed vacuum mixing equipment was fabricated at Hughes for low viscosity resin systems, which was used for preparation of premix and frozen encapsulation systems for evaluation.

9.3.2.3 Vacuum Mixing Evaluation

The vacuum mixer in Figure 9-27 was designed and built by Hughes to mix and dispense low viscosity resin systems for non-continuous encapsulation production. The mixer uses inexpensive disposable mixing containers, Figure 9-28, to reduce equipment clean-up. The disposable container remains sealed during mixing and degassing but is punctured inside the diameter of the outlet pipe when encapsulation is to begin. The puncture is accomplished by forcing down the pointed mixing shaft, Figure 9-29. The mixed resin is then metered into the encapsulation chamber, Figure 9-30. Monitoring of the degassing is achieved by the view port and light on top of the mixer, Figure 9-31.

The previously evaluated amine-cured epoxy resin system, Epon 825/HV hardener, was used to evaluate the mixing efficiency. Initial data on viscosity versus temperature, Figure 9-32 and Table 9-9 indicated that a processing temperature of 140° to 160°F (60° to 71°C) would yield an acceptable processing viscosity. The viscosity versus time at temperature, Figure 9-33 and Tables 9-10 and 9-11, of two different batch sizes (1200 and 120 gms) indicates that there is a definite exotherm that will limit the batch size for a given application time. It was determined that roughly 1000 grams of resin is required to encapsulate each stack of parts. A processing temperature of 140°F (60°C) was selected, based on viscosity at temperature versus time results in Figure 9-33, to provide a pot life of 40-60 minutes.

80-90527

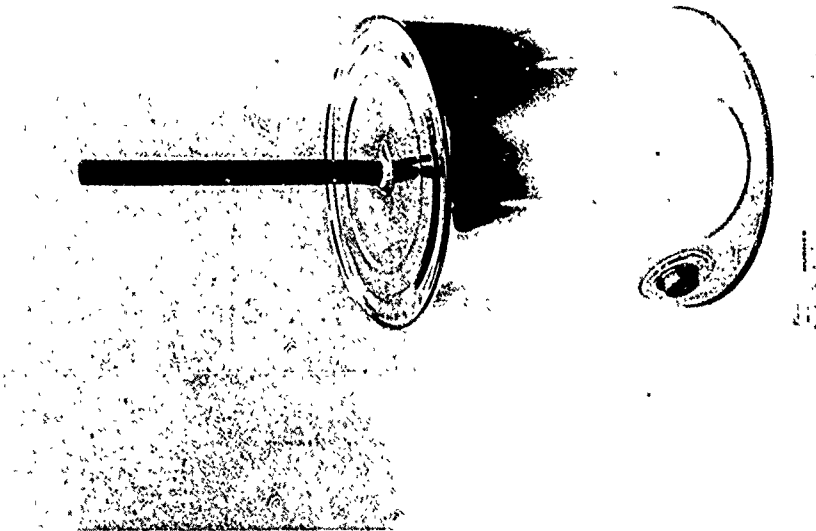


Figure 9-28. Disposable mixing container.

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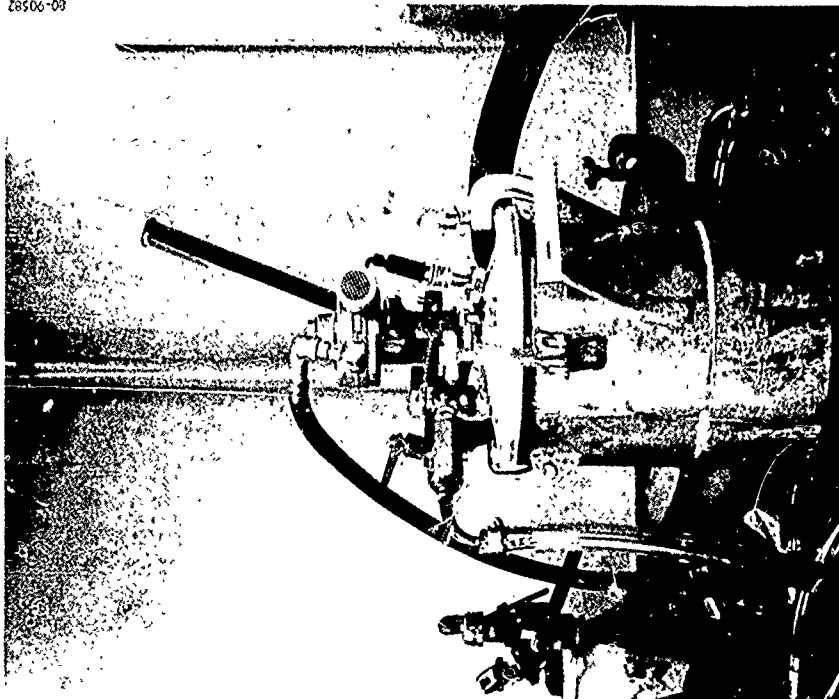


Figure 9-27. Vacuum mixing chamber.

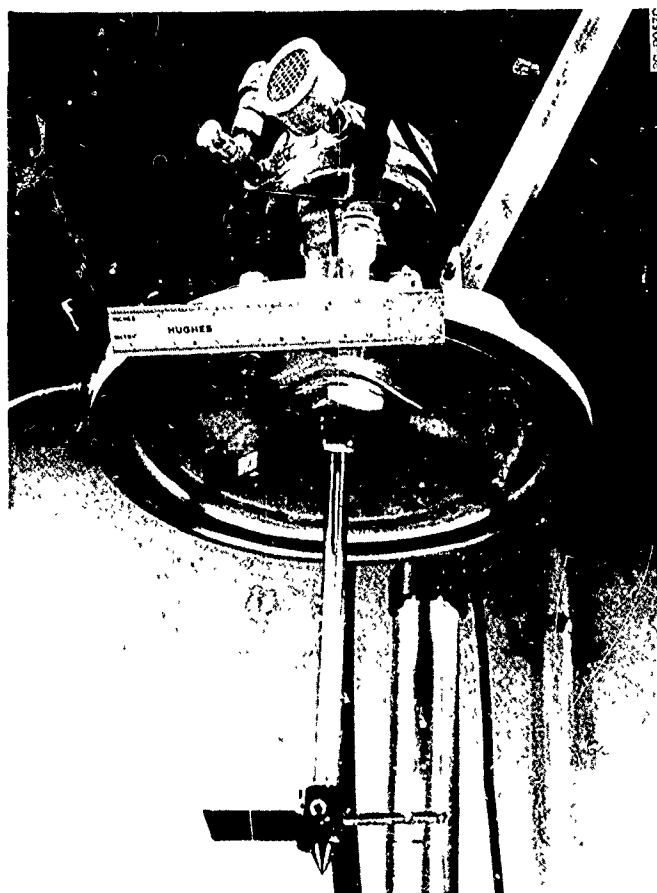


Figure 9-29. Pointed mixing shaft for puncturing mixing container.

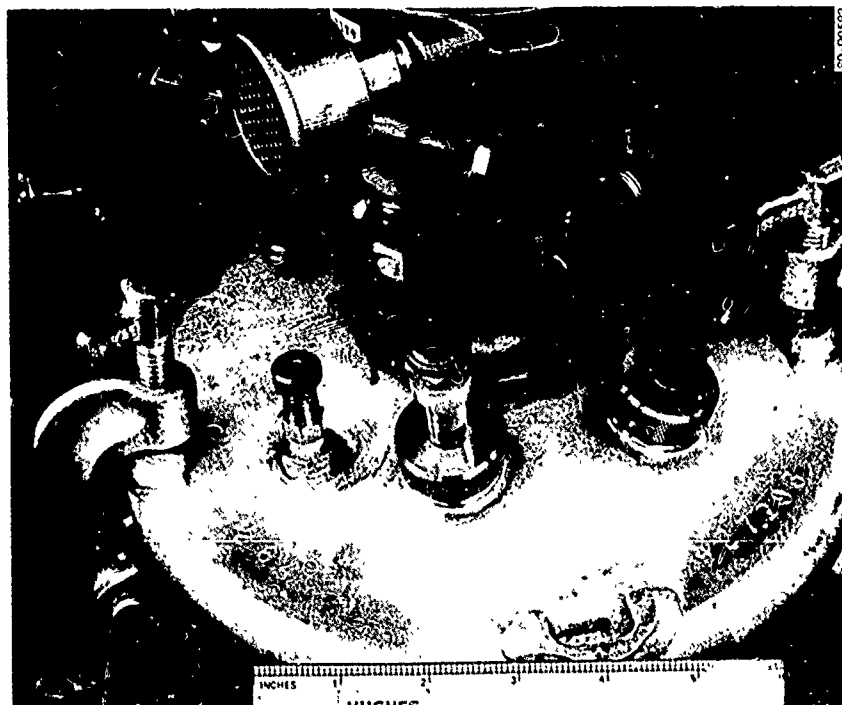


Figure 9-30. View showing light and viewport lens.

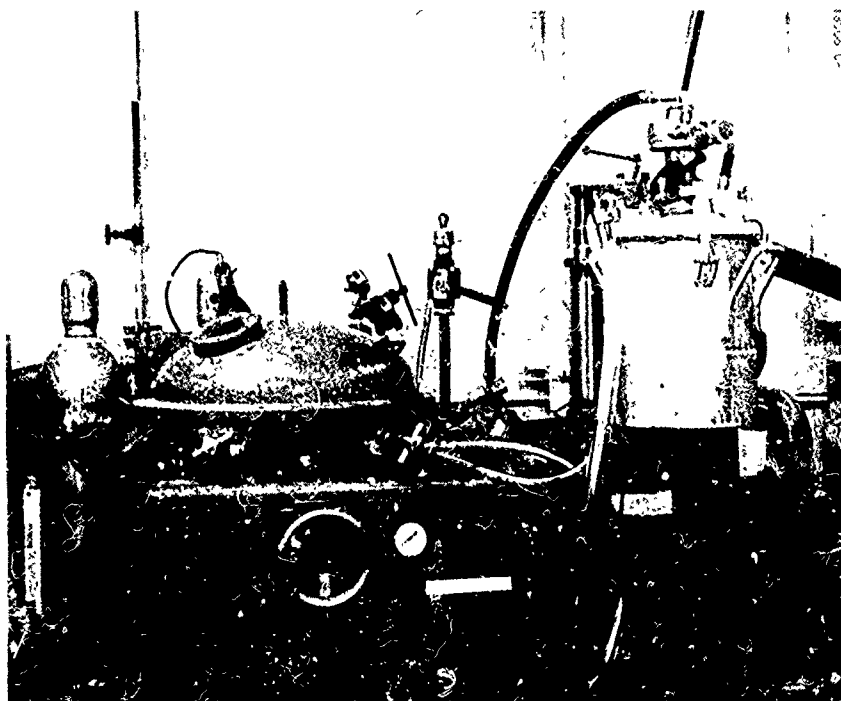


Figure 9-31. Mixing chamber and attached encapsulation chamber.

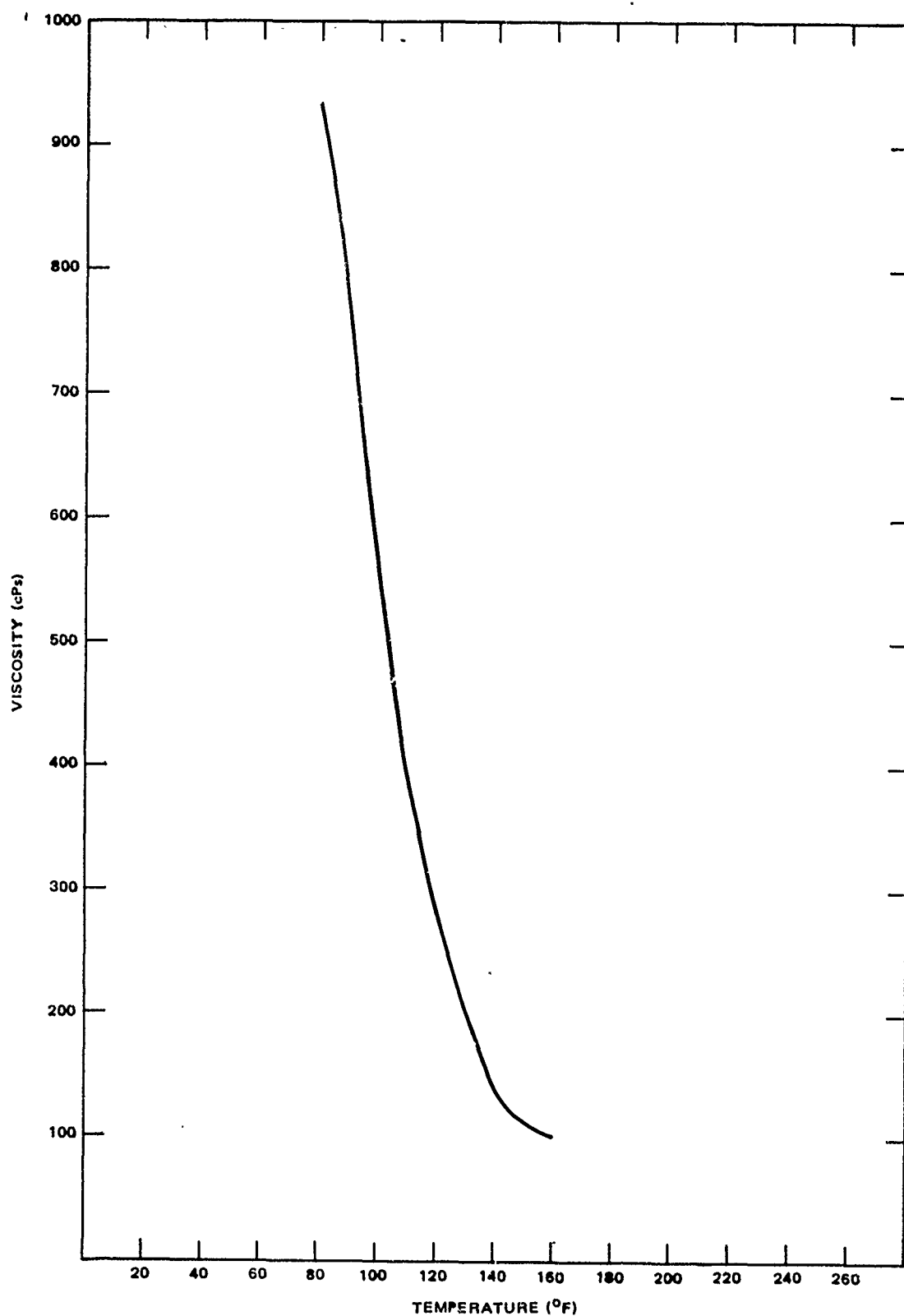


Figure 9-32. Viscosity versus temperature of epon 825/HV resin system.

TABLE 9-9. TEMPERATURE VERSUS VISCOSITY OF EPON 825

Temperature (°F)	RPM (RTV visc.)	Spindle	Reading	CPS
80	20	2	39	936
100	20	2	23	552
120	20	2	10.25	291
140	20	2	6	144
160	20	2	5	120

TABLE 9-10. TIME VERSUS VISCOSITY OF EPON 825 AND
HV HARDENER 120 GRAM BATCH SIZE

Temperature (°F)	Time (minutes)	RPM (RVT visc.)	Spindle	Reading	cPs
140	0	20	3	4.5	225
140	5	20	3	5.5	275
140	15	20	3	6.0	300
140	25	20	3	7.25	362.5
140	35	20	3	10.0	500
140	45	20	3	15	750
140	60	20	3	26.5	1,325
140	75	20	3	58	2,900
140	90	20	5	30	6,000
140	105	20	5	54	10,800
140	120	20	6	43	21,500
140	135	20	6	71.5	37,500
140	150	10	6	45	45,000
140	175	5	6	50	100,000

TABLE 9-11. TIME VERSUS VISCOSITY OF EPON 825 AND HV HARDENER
1200 GRAM BATCH SIZE

Temperature (°F)	Time (Minutes)	RPM (RVT visc.)	Spindle	Reading	cps
140	0	50	3	5.5	110
140	5	50	3	6.0	120
140	15	50	3	6.0	120
140	25	50	3	8.5	170
140	35	50	3	12.5	250
140	45	50	3	25.25	505
140	55	50	3	56	1,120
140	60	20	3	53.5	2,675
140	70	20	5	33	6,600
140	75	20	5	63	12,600
140	80	20	6	42	21,000
140	85	10	6	53	53,000
140	90	10	6	68	68,000
140	95	10	6	91	91,000
140	100	5	6	75.5	151,000

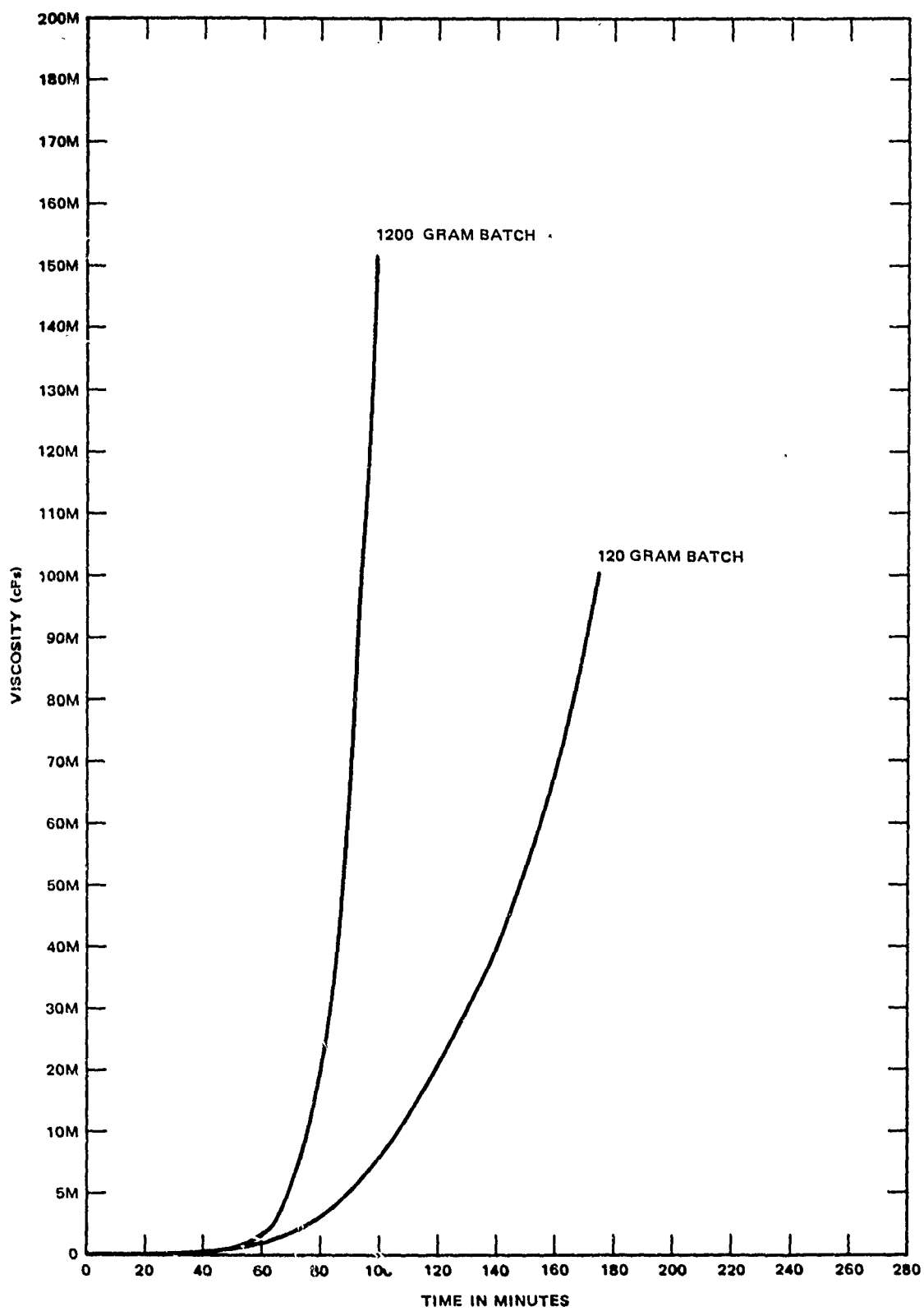


Figure 9-33. Viscosity versus time of two different batch sizes at 140°F.

The efficiency of mixing in the vacuum mixer was determined using procedures documented in Section 9.3.1.2. Two types of mixing procedures were evaluated.

- a. External mixing under atmospheric conditions using an electric mixer for five minutes. The mixed material was then transferred to the mixing chamber for degassing.
- b. Charging both components (catalyst and base) to the mixing chamber evacuating to 100 microns and then mixing under vacuum for ten minutes running the air-driven mix motor at one-third throttle.

Samples of each of the above mixed lots were taken from the top, middle and bottom and analyzed for uniformity of mix. Results demonstrated that both procedures equally and uniformly mixed the material. It was concluded that this equipment was capable of uniformly mixing low viscosity resins under vacuum without premixing.

9.3.2.4 Premix and Frozen Procedure

The procedure followed for premixing and freezing was as follows. Premeasured amounts of resin charged into the mixing chamber and mixed while degassing at 100 microns. The mixed material was filled into cartridges using care to prevent air entrapment. The filled cartridges were vacuum sealed in MIL-D-117E aluminized mylar bags then frozen in a dry ice/methanol bath.

The use of aluminized mylar bags was unique in this study since materials that were previously found unacceptable for use in a premix and frozen configuration were successfully packaged. Figure 9-34 shows a frozen cartridge on the left and a similar cartridge enclosed in a sealed mylar bag on the right. Figure 9-35 is a photograph of cured samples of RTV 627. The cured specimen on the right is full of gaseous voids caused by moisture contamination. Both specimens were prepared from premixed and frozen material, however, the sample on the left was protected by the bag during freezing and storage while the specimen on the right was not. All materials in this study were packaged in the bags to protect against moisture contamination. Protection against moisture is especially critical in materials used as dielectrics.

The use of a dry ice/methanol bath is preferred over liquid nitrogen in quick freezing for several reasons. First, the liquid nitrogen can cause fracturing of the aluminized mylar bag. Second, the resin may freeze so

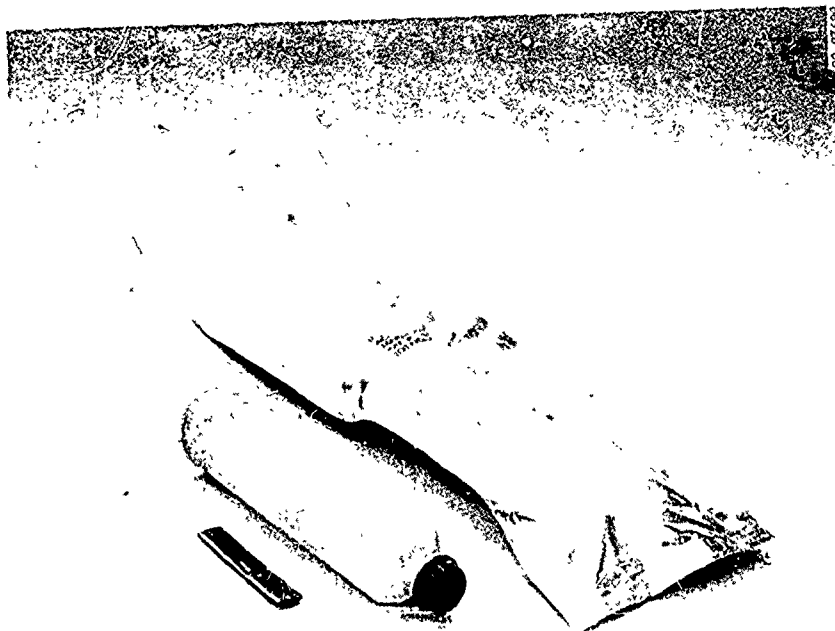


Figure 9-34. Frozen premix package, with and without aluminized mylar bag.



Figure 9-35. Cured premixed and frozen specimens of RTV 627. Frozen premix for sample on left was stored in aluminized mylar bag while premix for sample on right was stored in cartridge alone.

rapidly that the resin will pull away from the sides of the cartridge, instead of the plunger being drawn in, increasing chances of void formation in the thawing of the resin. Third, small companies often do not have the facilities to store or handle liquid nitrogen.

Three tests were performed on each frozen cartridge to determine the storage stability of the resin system, viscosity, stock work life and hardness. Viscosity was determined by thawing the material in a water bath, and measuring the viscosity with a model RTV viscometer. Stick work life was measured by placing a popsicle stick in a 100 gram mass of resin and determining the time at which the resin began exhibiting memory when the stick was pulled from the resin. The hardness was measured by use of a Shore A or D gauge on fully cured material. Viscosity and stock work life were used to evaluate the stability of frozen material while hardness was used to evaluate any effect on the cure of material.

Tables 9-12 to 9-18 are the storage stability test results. Results indicate that only RTV 11 and alumina filled Uralane 5753 were unable to be premixed and frozen. The RTV 11 is a problem because the cure mechanism continues to progress at -65°F . The filled Uralane 5753 is unstable because of the chemically bound water on the alumina will crosslink the urethane resin even at -65°F . A modification of the Uralane 5753 would make it possible to produce a filled frozen premix version. This change would involve the mixing of the alumina into the hydroxyl containing portion of the resin and drying the alumina in-situ before adding the curing agent.

The implementation of the above procedures for premixing and freezing these materials was accomplished by revising Hughes Process Specification HP 16-173.

The suppliers of premixed and frozen services listed under sources, Appendix 16.2.e were both visited to determine their capability. Both companies can handle the mixing packaging and freezing materials evaluated in this study.

TABLE 9-12. STORAGE STABILITY OF EPON 825/HV

Time at -65°F	Visc. (cPs)	Worklife (Hrs)	Hardness
0	2154	12-24	73D
1 wk.	3094	8-16	72D
2 wks.	2420	8-16	73D
3 wks.	2912	8-16	74D
7 wks.	2678	6-18	73D
12 wks.	2304	6-18	73D

TABLE 9-13. STORAGE STABILITY OF RTV 627

Time at -65°F	Visc. (cPs)	Worklife (Hrs)	Hardness
0	2328	3	69A
1 wk.	2300	2-1/2	69A
5 wks. 12 days	2570.5	2-1/2	68A
10 wks.	2667.5	2-1/2	69A

TABLE 9-14. STORAGE STABILITY OF RTV 615

Time at -65°F	Visc. (cPs)	Worklife (Hrs)	Hardness
0	5,626	6-12	28A
1 wk.	6,290	6	27A
4 wks.	10,695	6	29A
5 wks.	6,700	6	29A
11 wks.	6,461	6	28A

TABLE 9-15. STORAGE STABILITY OF RTV 11

Time at -65°F	Visc. (cPs)	Worklife (Hrs)	Hardness
0	174	3.4	46A
10 days	610	2	45A
13 days	2,139	1	45A
4 wks.	cured		

TABLE 9-16. STORAGE STABILITY OF Q3-6527

Time at -65°F	Visc. (cPs)	Worklife (Hrs)	Hardness
0	572	6-18	Gel
6 days	612	8-24	Gel
13 days	840	8-24	Gel
5 wks.	1,092	8-24	Gel
6 wks.	690	8-24	Gel
11 wks.	1,009	8-24	Gel

TABLE 9-17. STORAGE STABILITY OF FILLED URALANE 5753

Time at -65°C	Visc. (cPs)	Worklife (Hrs)	Hardness
0	112	2	72A
1 wk.	3472	1-3/4	72A
15 days	3909	50 min.	75A
22 days	4437	20 min.	75A
7 wks.	cured		

TABLE 9-18. STORAGE STABILITY OF SCOTCHCAST 255

Time at -65°C	Visc. (cPs)	Worklife (Hrs)	Hardness
0	17,200	>1 week	80A
1 wk.	19,340	>1 week	78A
2 wks.	13,800	>1 week	80A
3 wks.	12,900	>1 week	78A

An alternate approach of a collapsible cartridge rather than the plunger type was investigated, as shown in Figure 9-36. After thawing the premixed resin could be ejected without introduction of air by collapsing the cartridge. In actual practice, however, the end would pop off when pressure was applied to extract the resin. Also material was trapped in the convolutions.

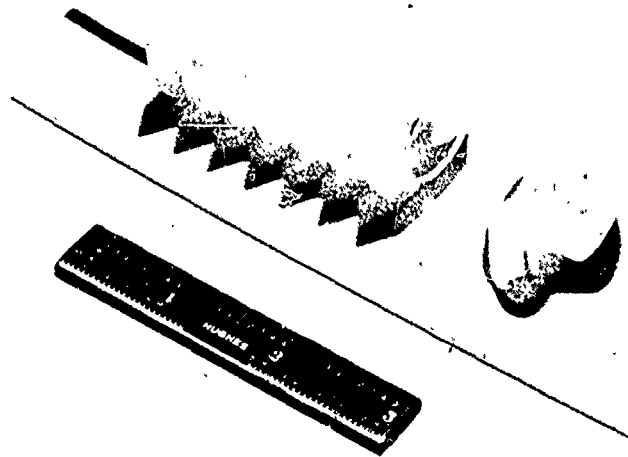


Figure 9-36. Collapsible cartridge for frozen premix.

9.3.2.5 Thawing Precautions

The thawing procedure of premixed and frozen materials is of great importance as it can affect pot life and viscosity. The thawing time and temperature must be controlled closely to obtain the maximum application life in the shortest thaw time. An increase in either temperature or thawing time will result in short application times.

The thawing of frozen cartridges can best be performed as follows. Remove cartridges from storage and thaw 30 minutes in a $212^{\circ} \pm 9^{\circ}\text{F}$ ($100^{\circ} \pm 5^{\circ}\text{C}$) heating block or water bath. If a water bath is used, caution

must be exercised to prevent the entry of water into the cartridge. One method of preventing the entry of water into the cartridge is to use a metal sleeve, closed at one end, with a diameter just large enough to allow the cartridge to be inserted to the lip of the plunger end. The sleeve is then placed in a water bath, closed end down. While the cartridge is thawing it is important to keep the cartridge vertical nozzle end down, to prevent air that may have been drawn into the cartridge during freezing from becoming trapped in the compound. Immediately after thawing a thin piece of metal or spatula blade should be inserted between the cartridge wall and plunger. The plunger is then forced down to exhaust air between the compound and plunger. When removing the metal or spatula a downward force should be exerted on the plunger to prevent reentrapment of air.

The forementioned thawing technique is preferred and was used in all testing in this work. Another method for thawing is the use of an oven. A determination of the optimum time and temperature is required because of variations in oven controls and air circulation.

9.4 IMPLEMENT A CONTINUOUS PROCESS FOR POTTING AND ENCAPSULATION

This section covers the actual assembly of equipment and the establishment of procedures to demonstrate a continuous process for potting and encapsulation of toroidal electromagnetic components, based on constraints listed in Section 9.0 and information developed in this program. "Potting" encapsulation of a component in a preformed cup, can be done with somewhat simpler but almost identical process to "encapsulation"; consequently, the later investigation covers both.

Background

The term "continuous" in the work statement was interpreted in the context of the constraints and limitations of production as applied to missile system magnetic components. As mentioned previously, the quantities encountered in missile production are orders of magnitude less than those

for, say, consumer television, so the continuous aspect must be scaled down accordingly. Limitations of time, equipment, molds, material and personnel dictated that the demonstration be a batch process. In a large production situation with adequate resources the technology demonstrated could be expanded into as continuous an operation as desired. In other words, it is felt that no basic limitation exists in the process and that it would be cost-effective over nearly any production rate. Equipment sizes and ratings must take into account the numbers and production rates of components to be encapsulated.

9.4.1 Transformer Selection and Modification

The toroidal transformer, previously designated as representative of this type for the MM&T program was selected, and a quantity of 100 ordered. As mentioned previously, several minor changes in the transformer packaging were done to facilitate the encapsulation process. The diameter of the terminal board was increased slightly to extend beyond the cylindrical surface of the finished part so that proper indexing or centering in the mold would occur. This ensured a uniform thickness of encapsulant over the winding which provided the necessary high voltage insulation requirement.

The first few transformers were fabricated, using mylar tape to anchor the windings and polyester tape, then the winding personnel were instructed to use the anerobic adhesive instead of the mylar tape as described in Section 10.3. Comparison of the two sets of samples showed that the adhesive method was practical and a significant improvement over the mylar tape. The winding personnel took appreciably longer to wind these transformers using the adhesive method because they did not have enough items to come up on the learning curve.

Another problem encountered was that the finished winding extended to the edge of the terminal board in some places so that the assembly would not fit into the mold. This problem was found to be due to two causes. First, the winding was larger than that allowed by specification. At first, this was thought to be due to the expertise of the winding personnel and the adhesive bonding, but researching back into the original procurements uncovered that this was a problem then also. It was found that certain

winding personnel could meet the size requirements and others could not. The solution to the present problem for the MM&T program was to omit two of the heavier wire windings and their taps, since the objective was to demonstrate a process, not encapsulate a transformer of a specific design.

Second, it was necessary to fabricate an alignment fixture which would center the winding on the round terminal board prior to soldering of the winding leads. This had not been a problem in the original procurements because the use of the hot vacuum-formed conformal cup would compensate for misalignment of the winding and terminal boards.

In order to conserve the quantity of transformers fabricated, 250 "dummy" transformers were fabricated, as shown in Figure 9-3. These consisted of a circular fiberglass board of the same size as the terminal board but without terminals, bonded to an annular ring which simulates the finished winding. These were used in the various molding systems to prove out the process before the much more expensive transformers were committed.

Mounting methods of the toroidal transformer were not considered in the original mold designs. In the toroidal configuration these usually consisted of either through-holes, or embedded, threaded studs or bolts in the center. The technology of mold design is capable of including mounting features as required.

9.4.2 General Procedure

The concept of a continuous process was modeled using the high voltage impregnating system Epon 825/HV. The basic equipment was; a table to clean the parts and place them in the RTV flexible molds, an automatic metering-mixing system with a heated vacuum tank for the resin, a vacuum system for degassing, and a heated, high pressure vessel in which to cure the parts. Each equipment was considered to be a work station. The parts were moved from work station to work station using an expediter with a cart to simulate a possible conveyer belt. It was found that the cart was quite adequate for the quantities used in this demonstration. Larger numbers of parts would necessitate a conveyor system.

Each of the machines were checked each day for proper operation. The mixer output of the automatic metering-mixing equipment was most carefully checked for proper proportion of resin and hardener, as changes in air pressure as well as temperature and several other parameters could affect the mixed resin. Encapsulation of a dummy part before and after each production run, processing them with the run, then sectioning and measuring hardness provided an in-process monitor and samples for later reference.

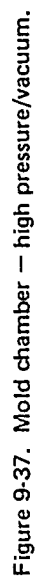
The parts were cleaned in the vapor degreaser to rid them of grease accumulated during fabrication. This was later upgraded to a degreasing followed by a vacuum bakeout with better results. The parts were then placed in the flexible molds, although metal molds or cups could have been used.

One finding was that if liquid RTV 11 was daubed into terminal recesses in the mold before the part was inserted, excess cured resin did not coat the terminals, simplifying and shortening the final cleaning operation.

The unmixed resin had been stored under vacuum, but the first mixed resin came out milky due to bubbles because the rotary mixer first mixed residual air into the resin/hardener. After the mixer was full of material, the mixed resin came out clear. This resin was poured into the molds at the mixer station, manually positioning the molds and controlling the amount poured.

The filled molds were then taken to the vacuum chamber station where entrapped air was removed, using vacuum and a vibrator motor to shake out any bubbles. The degassed parts were taken out of the vacuum chamber and placed into the pressure chamber for standard 16 hours at 165°F and four hours at 250°F under 500 psi dry N₂ pressure.

The simple small vacuum/high pressure chamber, Figure 9-37, which accomodates one part, was used as well as the large pressure chambers for purposes of comparison. These small size and lightweight individual chambers connected to a vacuum-pressure manifold, worked especially well. It is expected that their use would reduce the cost of the Epon 825/HV process because the use of large, separate pressure and vacuum chambers is not necessary.



After cure, the parts were removed from the pressure chamber and taken to the work bench where the parts were removed from the molds using small arbor press. The flexible rubber molds, with RTV 11 sealant in the terminal recesses, provided parts that needed virtually no excess material removal.

One problem did arise with the rubber molds, as described in Section 9.1.3. If the mold, during its fabrication, was cured at atmospheric pressure, then used at 500 psi at curing temperature, the parts came out with a sandpaper surface, due to compression of internal bubbles in the mold. New flexible rubber molds were made which were vacuum degassed and cured at 500 psi at ambient temperature. The encapsulated parts then came out smooth, showing that the internal bubbles were eliminated.

An alternate process to the vacuum degassing, after pouring and 16 hour cure at 500 psi, was investigated. Instead, after pouring in air, not vacuum, flexible molds were centrifuged for 5 to 10 minutes which apparently removed the bubbles, then cured for the required 16 hour time in a simple temperature oven.

The system of work stations with transport between stations, considering that the area available at Hughes was in a plastics laboratory involved in continuous production runs of other items, worked very well. The equipment at each station made the task flow smoothly without encountering bottlenecks, even though the other production runs had priority.

Access to the centrifuge for the alternate procedure was difficult because it was in a distant building, and many times the samples had to wait for higher priority work to be completed. This delay sometimes resulted in going over the pot life time, which resulted in entrapped air in a few samples.

9.4.3 Tentative Detailed Procedure

A step-by-step detailed procedure block diagrammed in Figure 9-38, is written in specification form for a continuous process, as demonstrated at Hughes, in compliance with the work statement, task 4C, Section 2.0. This procedure is based on Epon 825 with HV hardener; consequently, changes may be required for other encapsulant systems. Also changes may be

required for different volumes or configurations of the part. Normal documentation procedures at Hughes for material standards and processing would be to reference the applicable HMS and HP specifications; however, for the reader's convenience, the parameters are given here, to be used only as a guide. Actual implementation of this procedure for Hughes projects would require invoking of the required specifications.

<u>Equipment</u>	<u>Alternate Equipment</u>
1. Meter mix machine	
a. mixer proportioner	
b. resin storage in heated, vacuum tank	
c. hardener storage in tank at ambient temperature and pressure	
2. Vacuum chamber with internal vibrating platform	Centrifuge
3. Pressure chamber	Miniature pressure chambers
4. Flexible rubber molds	
5. Weighing scales	
6. Vapor degreaser	

Materials

- a. Epon 825, within expiration date
- b. HV hardener, freshly mixed
- c. Finger cots or clean, lint free gloves
- d. RTV-11

Step 1

The parts to be embedded and molds shall be thoroughly cleaned in a vapor degreaser to remove contaminants (grease, oil).

Step 2

Parts shall be placed in the molds using gloves or finger cots. In this procedure, the molds establish the final dimensions and surface smoothness. Terminals on the parts fit into close fitting holes in molds which shall be filled with liquid RTV 11 to minimize excess material removal.

Step 3

The meter-mix machine shall be turned on and the temperature of the resin tank checked. The temperature shall be $140^{\circ}\text{F} \pm 5^{\circ}\text{F}$ ($60^{\circ}\text{C} \pm 3^{\circ}\text{C}$). The mix ratio shall then be checked for proper proportion by weight. Mixture ratio shall be 17 parts hardener to 100 part Epon 825 by weight. Mixed material shall be drawn from the mixer until it is clear, without cloudiness or bubbles. If meter-mix equipment has a preset shot adjustment, this adjustment shall be set.

Step 4

The vacuum chamber and pressure chambers shall be checked for proper operation, including testing of the vibrating platform. Liquid or high pressure nitrogen levels shall be checked to ensure that an adequate supply is available throughout the process.

Step 5

Molds shall be filled with mixed resin by moving mold under flow tube. A dummy part in a mold shall be the first poured and identified by suitable marking. At the conclusion of the pour, the last shall be a dummy part suitably identified. (In a large production run, a dummy part may be taken for every 100 parts to check control of the process.) A dummy part shall be poured after every refilling of resin and/or hardener tanks.

Step 6

After filling, the molds shall be placed on a tray and placed on the platform in the vacuum chamber. The poured molds, including the dummy parts, shall be degassed in the vacuum chamber at 100 microns or less for 10-15 minutes, while vibrating the platform.

Step 7

Remove the molds from the degassing chamber and place in the pressure chamber.

Step 8

Cure the parts in the pressure chamber in a 500 psi dry nitrogen atmosphere at 165°F (74°C) for 16 hours followed by a post cure of 4 hours at 250°F (122°C).

Step 9

Allow molds to return to ambient temperature, then remove part carefully using small arbor press with fixture to protect the flexible mold.

NOTE 1

If suitably equipped, the molds can be filled within the vacuum chamber by connecting the meter-mix mixed resin output directly to the resin inlet of the vacuum chamber. Manipulation of the molds and fill tube through the vacuum interface, allows the parts to be filled with resin under vacuum, removing one handling step and combines steps 5 and 6 above.

NOTE 2

The use of a vacuum to remove entrapped air is the method used during the demonstration to force air out of the liquid mixed encapsulant. An alternate to the vacuum-pressure process is to use a centrifuge which separates lighter air bubbles from the heavier but thin resin. Processing time is speeded up because the vacuum and pressure chambers are not required. Only an oven is required. The main disadvantage of this technique is that each filled mold must be counter-balanced exactly (to within ± 1 gram). The gross counter-balance can be another part and mold, but the weight difference must be trimmed using small, added weights to get the exact balance, before rotating.

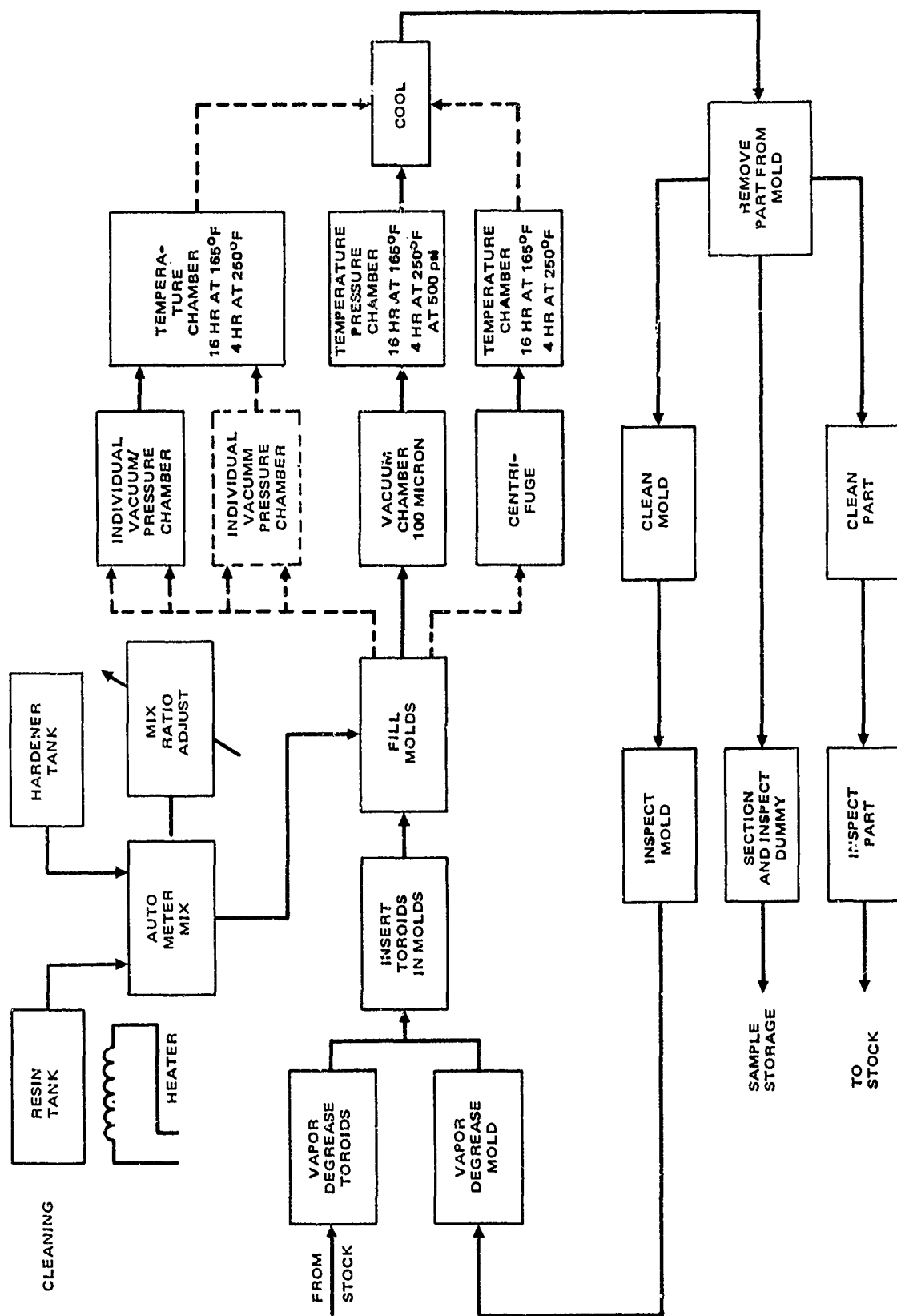


Figure 9-38. Block diagram of continuous potting and encapsulation procedure.

10.0 STRUCTURAL PARTS

Four areas were investigated and evaluated from structural considerations, namely, shielded bobbins for high voltage transformers, thermoplastic and thermosetting plastics for coil supports, anchoring of windings within transformer coils, and C-core banding. As for the previous tasks, the emphasis was on applications to high reliability components.

10.1 SHIELDED BOBBINS FOR HIGH VOLTAGE TRANSFORMERS

10.1.1 Voltage Gradient Control Consideration

An effective method of gradient control which can be used for high voltage, fine wire windings on bobbins is conductive shields, one biased at ground potential next to the core and the other biased at the average high voltage of the winding. This shield provides an equipotential plane around the winding and permits the maximum gradient to occur across a solid homogeneous insulation material.

Figure 10-1 shows three configurations of a bobbin with shields in cross-section. On the left is a typical shielded configuration with the outer shield held at ground potential and the inner shield at the high voltage potential, producing the maximum gradient across the bobbin material. A problem of this approach is the high gradient stress region existing at the edges of both shields. Since the shield is considered very thin, this gradient may be quite high and with some manufacturing technologies may consist of a feathered edge which would increase the gradient even further. A method of decreasing the possible gradients existing from this feathered edge is the use of gradient control wires terminating the edges of the shield as shown. The

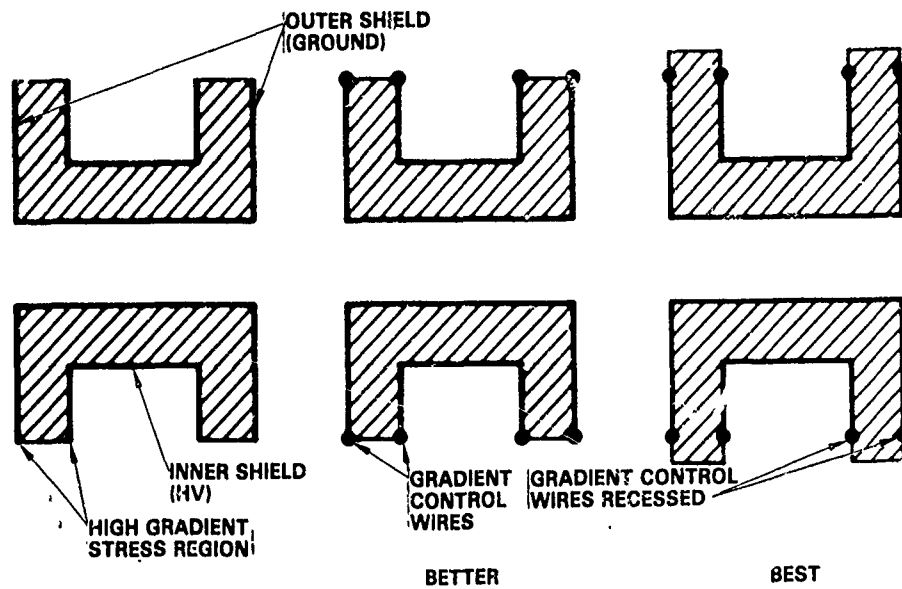


Figure 10-1. Shielded bobbin cross-sections.

addition of this wire reduces the gradient to a known value, but the problem of the maximum gradient occurring at the interface between the edge of the bobbin and the encapsulation compound still exists. The best method is shown in the right-hand figure, which extends the bobbin flanges slightly so that the interface of the bobbin and the encapsulation material is extended away from the maximum gradient directions. Based on this approach, the manufacture of high voltage shielded inductors for a high reliability electromagnetic component was examined by modifying a selected bobbin structure to include these two equipotential surfaces. For the purposes of evaluation and comparison with an existing electromagnetic component, the bobbin configuration shown in Figure 10-1 was designed so that it could be substituted for the double coil assembly molded by the LIM process described in Section 9.1.5. Actual comparison of these shielded bobbins with the LIM configuration by functional and environmental tests was not possible because of unanticipated delays and problems encountered in the molding process of the shielded bobbins. However, much was learned and the approach reported herein appears viable for high voltage applications.

10.1.2 Bobbin Design

Equipotential surfaces which are integral with the bobbin have two functions. First, reduction of voltage gradients by electrostatically shielding the fine wire winding over those which would exist with the fine wires alone; and second, elimination of possible voids initiating corona which might occur between the encapsulation and the bobbin surfaces. These surfaces are meant to alter the voltage gradient which exists between the winding and the core or between adjacent bobbins in order to reduce the probability for corona discharge. Bobbins fabricated in this investigation are primarily constructed to prevent dielectric breakdown between the windings and the core or between adjacent windings. The peak difference in potential between the winding and core could exceed 12 kilovolts. A sketch is shown in Figure 10-2.

In this modified bobbin, the dielectric material between these equipotential surfaces can be the same material used in conventional bobbins. The equipotential surface adjacent to the winding should be embedded in the insulation to provide additional high voltage protection from the windings and to provide better mechanical or handling protection. Embedment is necessary to prevent possible shorting of the conductive surface with an abraded winding. Also, accurate control of the voltage gradient would not only require embedment, but may require precise depth control of the conductive surface. The inner surface next to the core need not be embedded.

When precise embedment depth control is not a requirement, overcoating the surfaces with a dielectric provides the necessary protection. The usual overcoating restrictions apply. A rigid overcoating material should not be applied over a flexible coating, or upon exposure to rapid or extreme thermal changes, cracking and flaking of the overcoating material may occur. The same is true of a rigid equipotential coating relative to the bobbin substrate. Stressing may cause cracking of the equipotential coating surface.

NOTES:

1. DARKENED AREA INDICATES BREAK IN COATING SURFACE
2. BREAK IN LOW RESISTANCE COATING REQUIRED TO ELIMINATE SHORTED TURN EFFECT

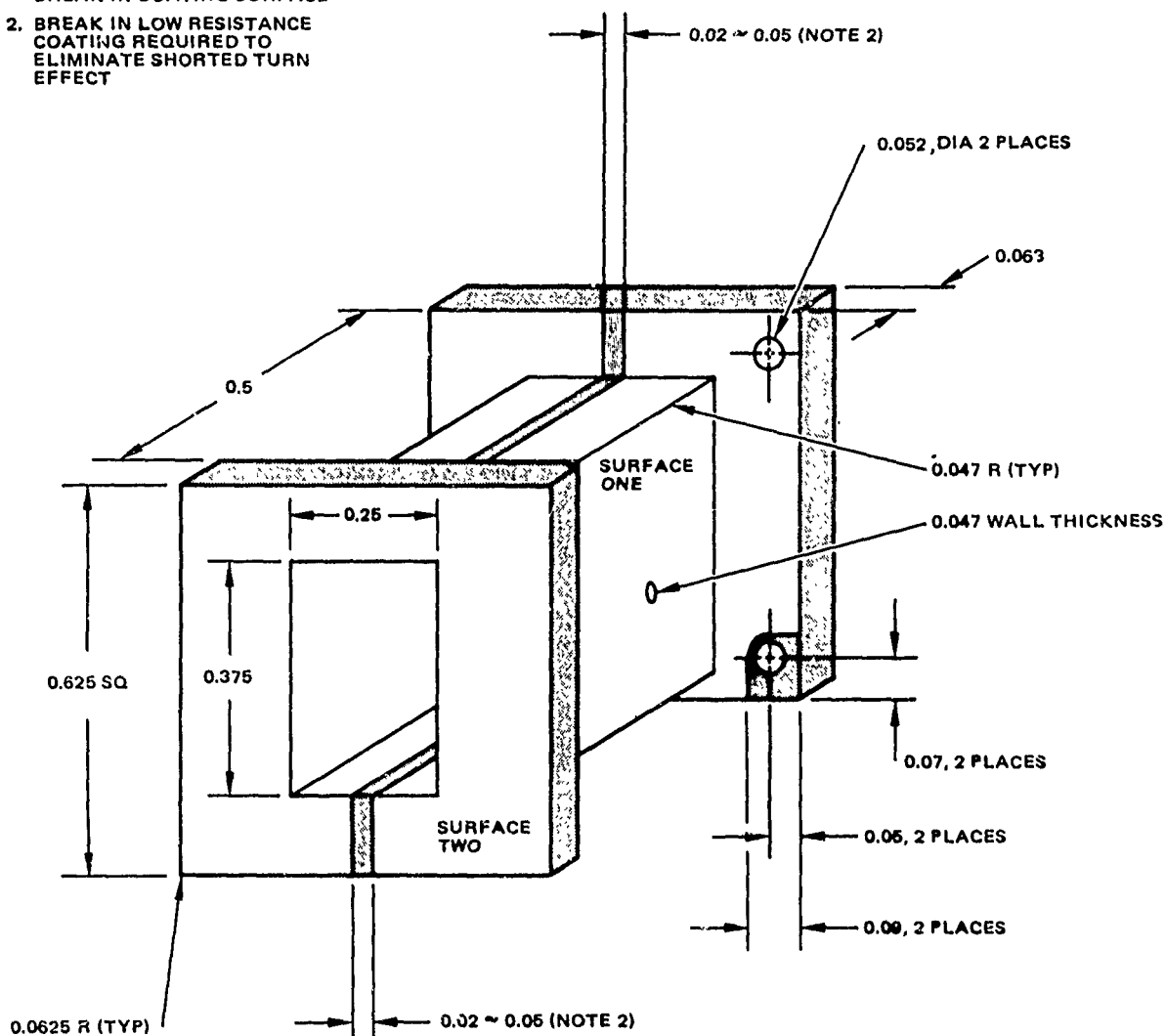


Figure 10-2. Dimensioned sketch of fabricated bobbin showing two equipotential surfaces.

These equipotential surfaces and electrical connections to them must be constructed so as not to destroy or limit the high voltage integrity of the bobbin insulation. Especially important on miniature, or subminiature high voltage bobbins, design configurations must prevent surfaces with sharp points or thin cross-sections with feather edges and should maximize the insulation distance between fine wires connecting the equipotential surfaces. Rounded edges are essential to reliable long-term operation.

These thin equipotential surfaces as designed will reduce the gradient and will not substantially reduce the winding volume over that of unshielded bobbins.

Rounding the edges of the flanges as shown in Figure 10-3 is another method of removing the bobbin-encapsulant interface out of the maximum gradient direction as discussed in Section 8.5.4.

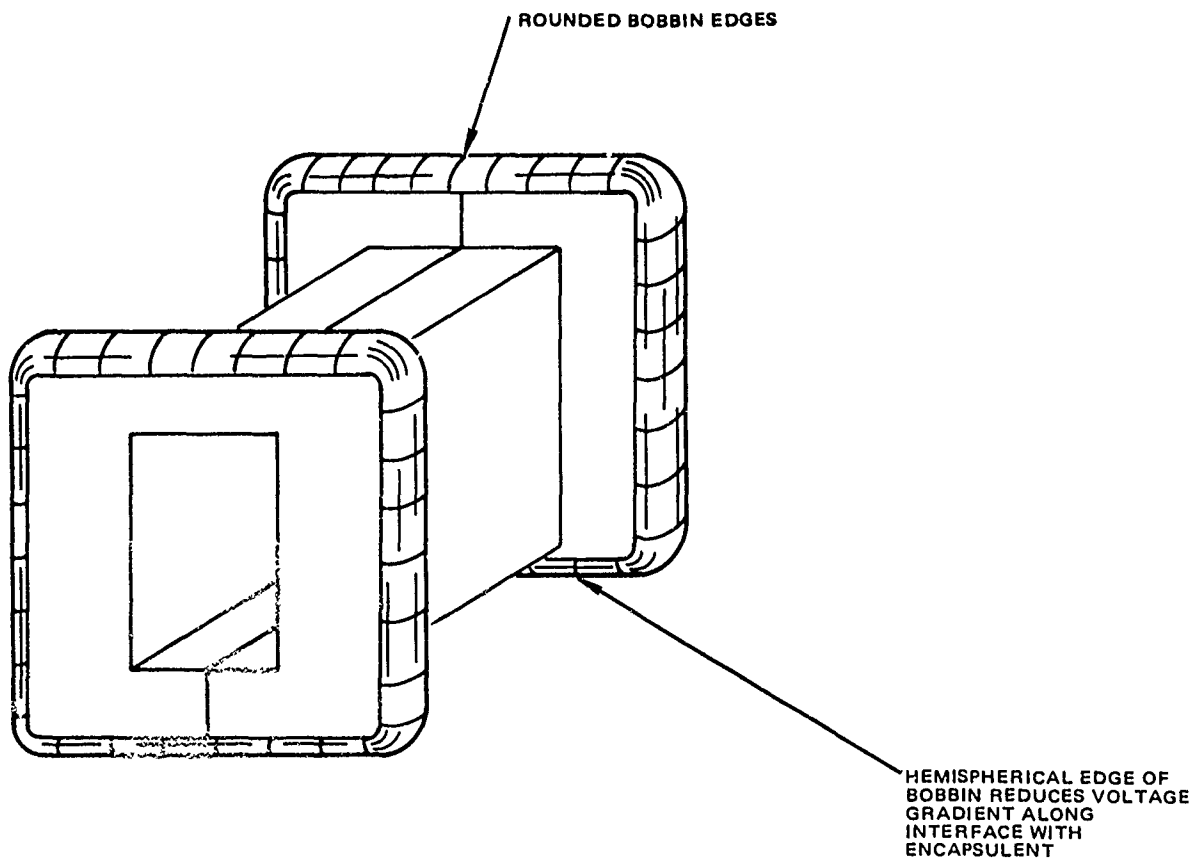


Figure 10-3. Improved bobbin

10.1.3 Types of Equipotential Surfaces

The processes listed below for fabricating the equipotential surfaces were investigated.

1. Metallic surface coating
2. High resistance spray coating
3. Potting of wire mesh screen or other contour
4. Molding or embedment of EMI attenuating plastics.

Modified bobbins have been successfully made using the first two methods. The last two processes would require more time to develop for manufacturing plus elaborate and costly tooling would be needed. The wire mesh potting method requires that the mesh be held securely in place under the proper tension on the mold during molding of the bobbin. The edges of the high voltage mesh must be terminated properly to prevent sharp points occurring. Lastly, the time required to lay up the mold is greater than with the other processes.

The molding of conductive plastic requires a second molding operation when injected over a conventional molded bobbin. This is considered to be a practical method for making the equipotential surface as long as this plastic is compatible with the substrate.

10.1.4 Molds and Processes

10.1.4.1 Mold Types

The usual procedure for making bobbins requires fabrication of the mandrel and sides separately followed by a bonding operation. When forming equipotential surfaces, this would require interconnection of the surfaces to one another, introducing additional problems. This complexity can be eliminated through the use of one or two step molding or casting processes, especially when the terminals and surfaces can be included in the mold design.

The following molds have been considered in this investigation:

- a. Vacuum/pressure casting mold
- b. Transfer mold
- c. Injection mold
- d. Expansion mold

a. Vacuum/Pressure Casting Method

In the vacuum/pressure mold, the part is cast by vacuum degassing the resin in the mold and subsequently pressure curing. This is a low to moderate yield casting process depending upon the materials to be used and the mold itself. This type of casting process is generally used with low viscosity resins such as Epon 825, which was used to make bobbins in this investigation.

A mold was designed and used to fabricate the L-bobbins studied in this investigation. A sketch is shown in Figure 10-4. The mold was designed to be versatile so that various configurations and processes could be evaluated. The mandrel may be removed from the baseplate by loosening a screw and tapping on two alignment pins underneath the baseplate. The two front pins (providing the terminal holes) may be removed. The center plate can be split into halves facilitated by a jack-screw. Reversing the front plate of the mold, allows alternate pins to be used. Terminals may replace the pins in the mold if desired but with this mold design, cleanup around the terminals will be necessary. A dimensioned sketch of a bobbin fabricated from this mold is also shown in Figure 10-5 and an actual part in Figure 10-6.

A bobbin cast from another vacuum/pressure mold is shown before addition of the equipotential surfaces (Figure 10-7). Figure 10-8 shows a similar bobbin with aluminum equipotential surfaces. The gap is necessary to prevent the shorted turn effect on the winding. Figure 10-9 is another bobbin, with high resistance equipotential coatings. No gaps are required because the current flow due to the shorted turn effect would be negligible. The terminals provide connections to the equipotential surfaces.

The process used in this investigation for fabricating the bobbin shown in Figure 10-5 is listed in Table 10-1, along with the time to manufacture various quantities. The scheduling does not include the fabrication of the equipotential surfaces, assumes the learning curve is no longer a factor, and takes into account batch type processes (e. g., oven curing).

b. Transfer Molding Method

The transfer and injection molding methods for making the modified bobbins are high production operations both potentially

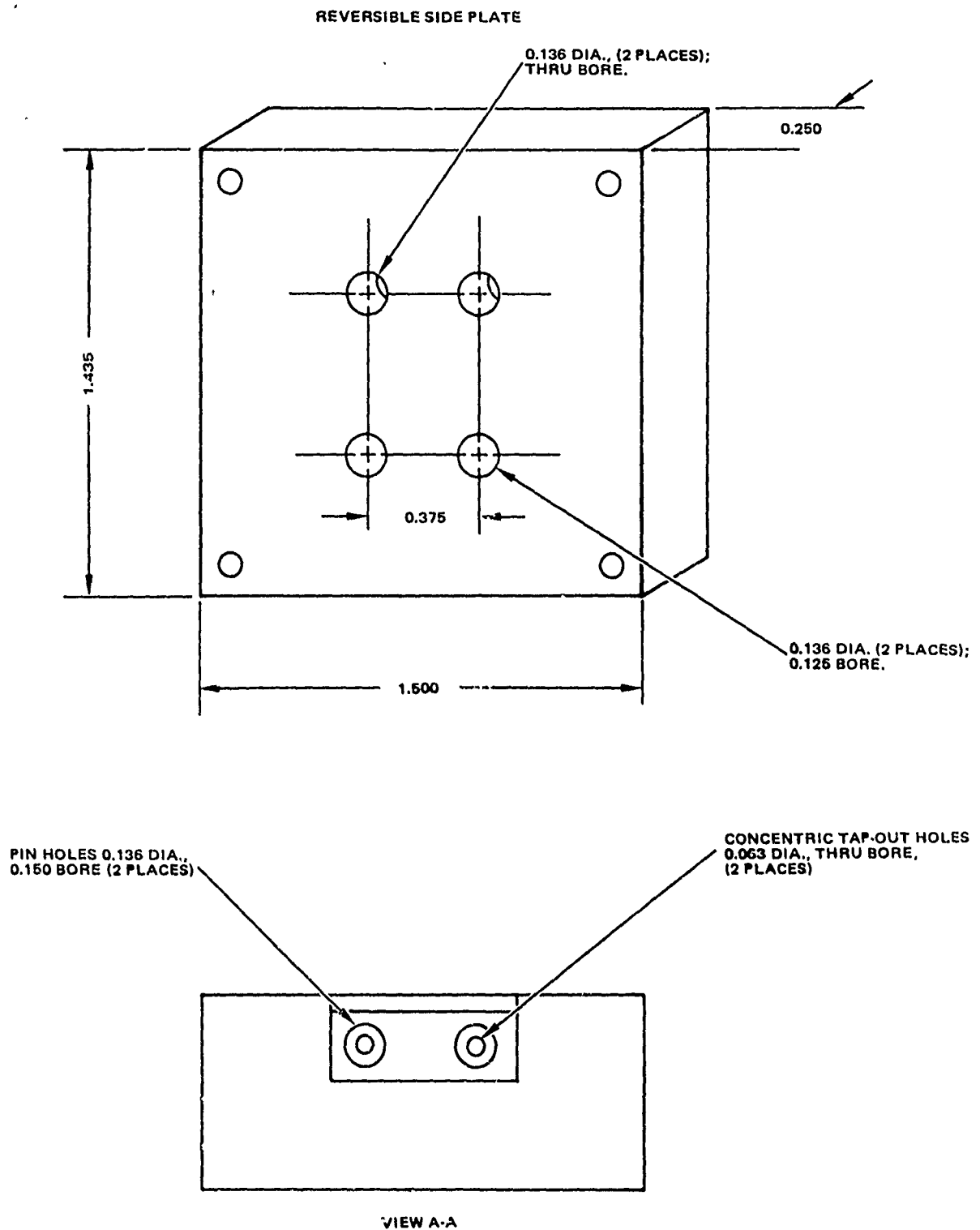


Figure 10-4. Dimensioned sketch of fabricated vacuum/pressure casting mold (sheet 1 of 2)

Exploded view diagram of a vacuum tube socket assembly. The diagram shows the following components and dimensions:

- TOP PLATE:** Dimensions include 0.250 (thickness), 0.060 (gap), 0.560 (height), and 0.425 (width of central feature).
- CENTER PLATE:** Features a central hole for a jack screw. Dimensions include 0.425 (width of central feature) and 0.060 (gap).
- BASE PLATE:** Dimensions include 0.200, 0.250, 0.050, 0.375, 0.625, 0.660, 0.610, 0.270, 0.110, 0.375, 1.500, and 0.0625 (radius).
- Labels and Features:**
 - TAPPED HOLE TO SECURE SIDEPLATE, 4 PLACES
 - ROUND EDGES AT 0.030, 9 PLACES.
 - FINE GROOVES ARE ALONG CAVITY EDGES FOR INSTALLATION OF GRADIENT CONTROL WIRES (4 PLACES).
 - ROUND CORNERS AT 0.0625 RADIUS, 8 PLACES.
 - 1/2° angle
 - 27.5° angle
 - 0.500 dimension
 - TAP-OUT INSERT (DRILL BLANK)
 - LARGE ALIGNMENT PIN HOLE
 - REMOVABLE ALIGNMENT PINS AND SECURING SCREW
 - SMALL ALIGNMENT PIN HOLE.
 - TAPPED HOLE TO SECURE TOOLING PLATES.
 - PIN, .135 DIA., (2)

10-9

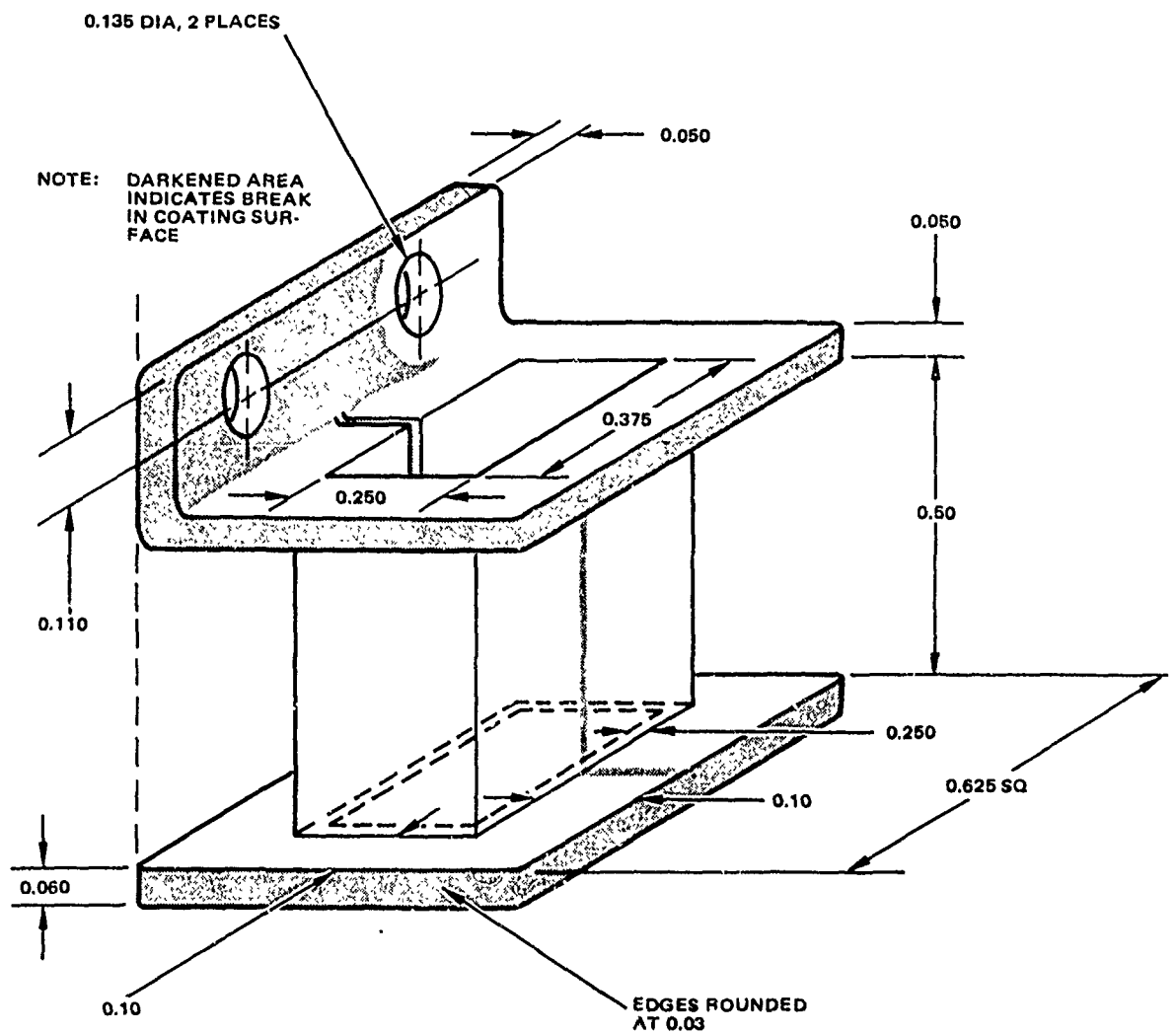


Figure 10-5. Dimensioned sketch of L-bobbin.

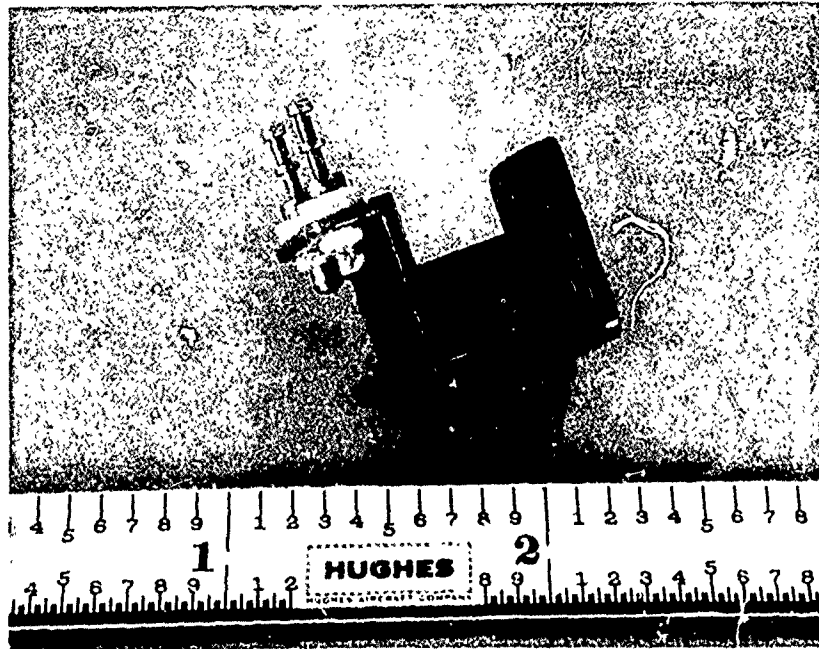


Figure 10-6. "L" shaped bobbin made from vacuum/pressure casting process.

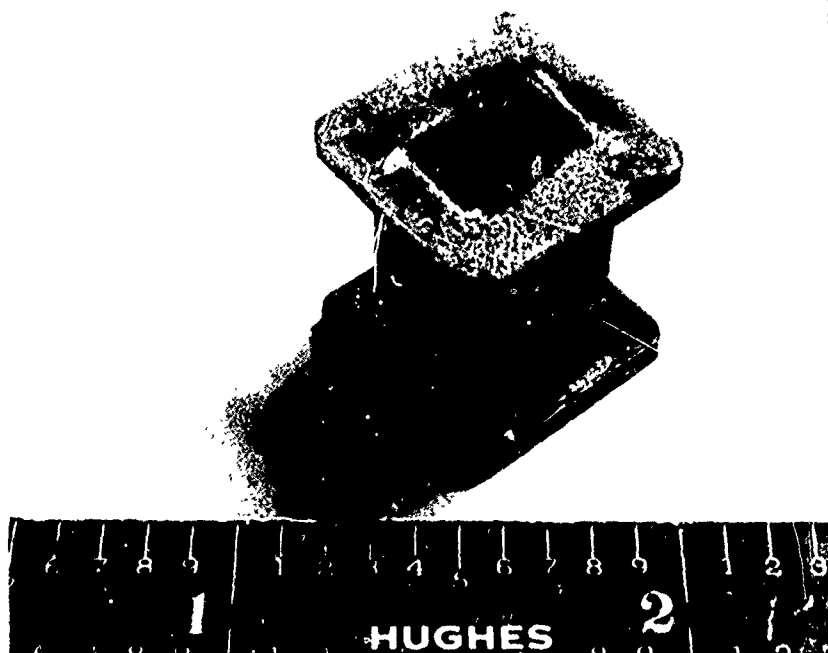


Figure 10-7. Conventional bobbin made from vacuum/pressure casting process.

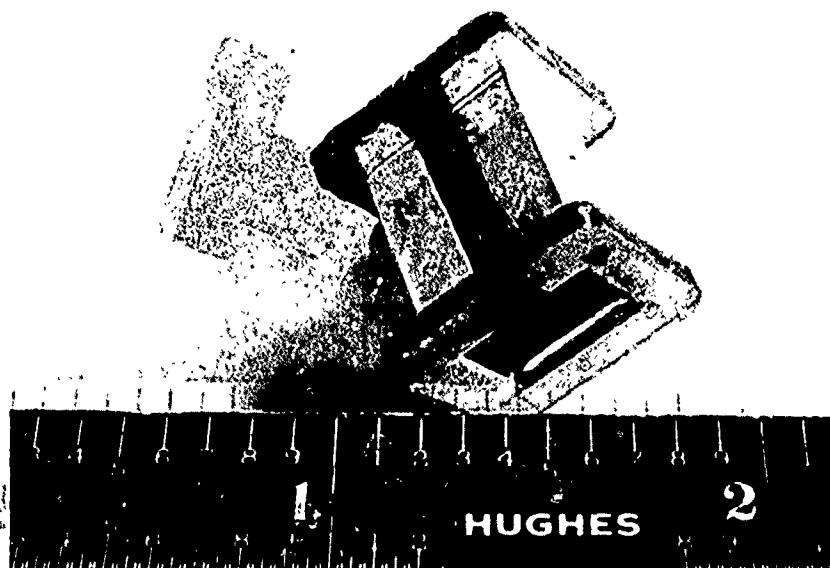


Figure 10-8. Molded bobbin with equipotential surfaces of vacuum deposited alumina.

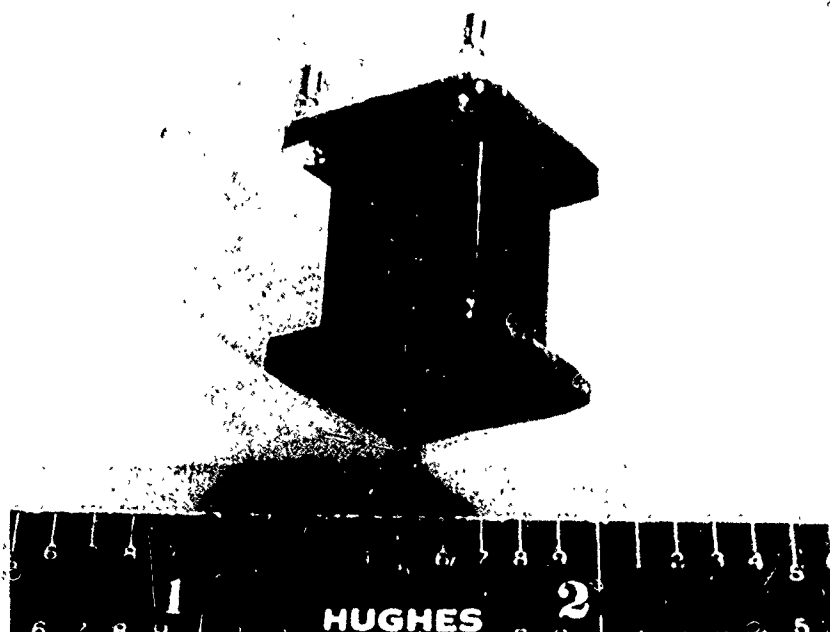


Figure 10-9. Molded bobbin with high resistance equipotential surfaces.

TABLE 10-1. MOLD PROCESS TIME ESTIMATES

Step	Process Description	Completion Time (hrs)				
		Number of Molds				
		1	2	3	4	5
1	Clean, mold release and dry	0.5	0.65	0.80	0.95	1.1
2*	Load mold with polyester mat and/or fiberglass or equivalent and assemble tooling	1.0	1.8	2.6	3.4	4.2
3	Seal exposed screws, pins, holes, etc., with RTV 11 or equivalent to facilitate cleanup (optional)	0.3	0.45	0.6	0.75	0.9
4	Bakeout mold in 200 to 250°F oven	8.0	8.0	8.0	8.0	8.0
5	Mix material, Epon 825 HV or alternate low viscosity resin system and place in reservoir	0.2	0.2	0.2	0.2	0.2
6	Mold parts					
	a. Vacuum degas	0.7	0.7	0.7	0.75	0.75
	b. Pressure cure in nitrogen at 500 psi and at 190°F	12.0	12.0	12.0	12.0	12.0
	c. Post cure at 250°F	4.0	4.0	4.0	4.0	4.0
	Total Handling Time only	2.0	3.1	4.2	5.3	6.4
	Total Process Time	26.7	27.8	28.9	30.1	31.2
*When fine wires for gradient control are to be installed in the mold as shown in Figure 3, add 0.5 hour to the total handling time for each additional mold.						

capable of providing a much greater yield than the vacuum/pressure technique. Both types of molding operations are usually meant for high viscosity/high pressure resin systems (e.g., roving filled thermosets) and require careful planning in order to select the necessary processing parameter values.

In transfer molding, the charge (molding material) is transferred under pressure by a hydraulic ram from a pot through runners and gates into the cavities retained in a closed mold. Usually the charge is preheated before being placed in the pot, so that less pressure is required and reduced cycle time is obtained. Since the transfer molding method is capable of achieving higher pressures and is more versatile than the injection molding method, it offers the following distinct advantages:

1. Better dimensional stability on close tolerance intricate and complicated parts.
2. Allows greater choice of thermosetting materials (generally better heat and chemical plastics resistance and electrical properties than thermoplastics).
3. Permits higher density resins, allowing improved overall dielectric and stiffness properties.
4. Permits substitution of different cavities into mold (family plunger mold) and is an economical way of assembling small molded parts. For example, equipotential surfaces might be formed separately and later assembled to the bobbin.
5. Produces parts with little flash and therefore reduces finishing costs.

A transfer mold has been designed for making conventional bobbins which would require a metallic or high resistive coating to obtain the equipotential surfaces as shown in Figure 10-10. Designed to produce two parts at once, the mold is representative of the type involved. Modifications are needed to readily mold the terminals, mesh or wires along the edges. If the chamber configuration, injection runners and gates are properly integrated into the mold design, many more parts could be produced at once (e.g., 6 to 10 parts).

This transfer mold may also be used as one part of a two stage transfer molding operation for making conductive plastic equipotential surfaces. Bobbins would be fabricated slightly undersize in the first transfer molding operation. Once these parts have set, they are placed in another mold located by ejector pins. The equipotential surfaces are formed by encapsulating parts of the bobbin with a thin high resistive material such as an EMI shielding plastic.

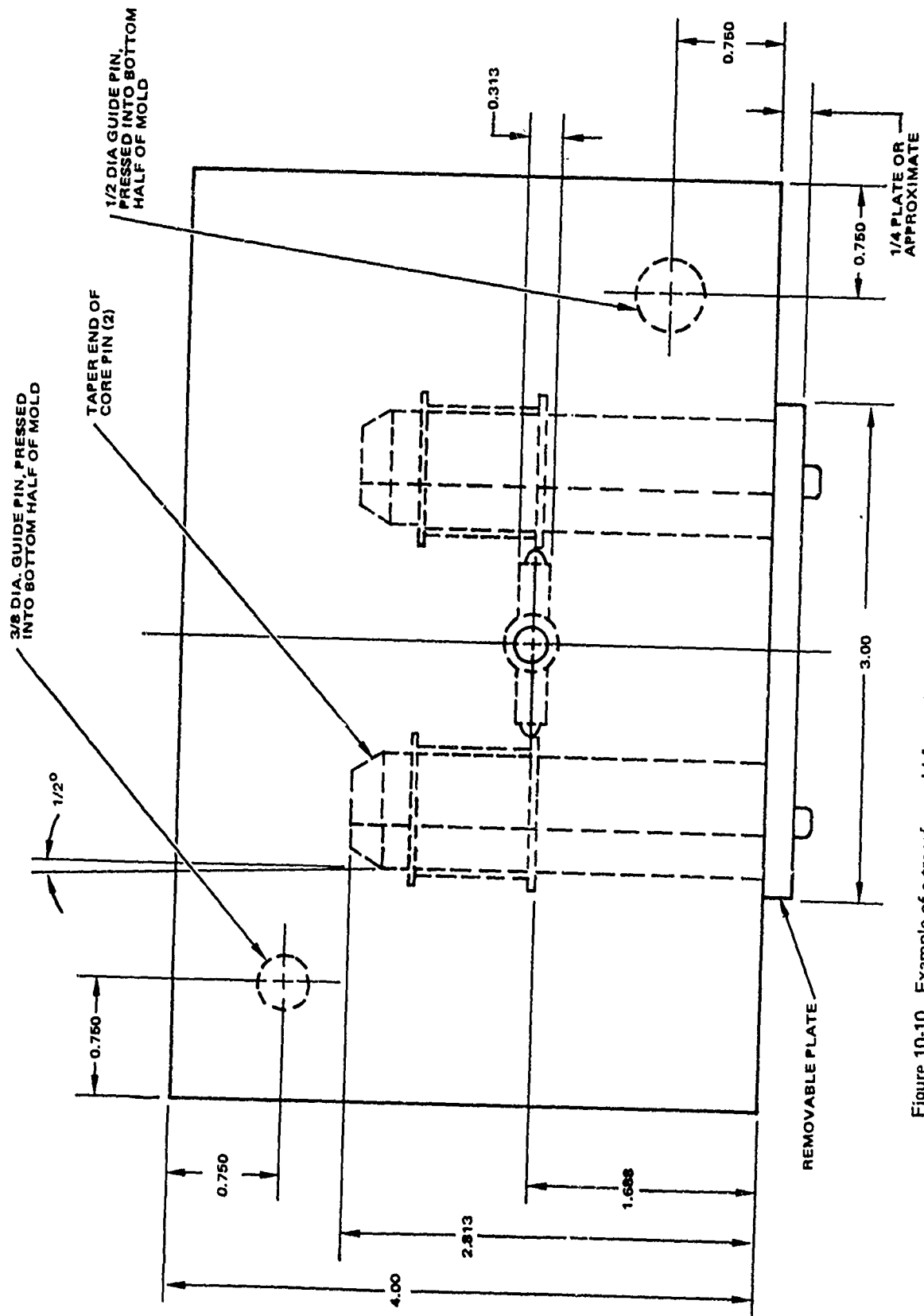


Figure 10-10. Example of a transfer mold for making bobbins (dimensions are in inches) (sheet 1 of 2).

Processing times cannot be stated specifically since suitable transfer molding materials, as well as the bobbin design and mold design has not been established. Once these criteria have been met the following steps should be taken:

1. Determine the extent the materials processing parameters may be varied (i. e., pressure or flowrate, thermoset time, degree of B-stage, etc.)
2. Determine parts of assembly which cannot be transfer molded, if any
3. Determine number of parts to be produced
4. Decide whether or not a one or multiple step transfer molding operation is preferred - examine the cost trade-off
5. Design mold - cavity shape, geometric distribution, ejector pin location, etc. This may require redefining above criteria
6. Set process parameters - temperature, pressure, heating cycle, mold thermoset time.

c. Thermal Expansion Molding Method

The last mold considered as applicable to making the modified bobbins is the thermal expansion mold. This is an experimental mold, unlike the other molds, in that a low pressure prepreg would be used to fabricate the bobbins in one step. A prepreg has advantages over the conventional bobbin substrates as discussed in the next section. This type of mold, if successful, would be the easiest to work with.

The expansion mold is a close tolerance mold which when heated applies pressure to a prepreg. It would consist of carefully selected, reliable expansion materials on a low expansion substrate. The design also involves choosing the proper mechanical restraints in order to set up the desired stresses on the laminate. A shielding contour may be a part of this laminate structure.

The expansion mold is complex and was not designed. The estimated yield for using this mold is not clear but may be up to 10 times the vacuum/pressure casting yield. The fabrication steps using the expansion mold are listed below:

1. Obtain prepreg, punch out desired shape and thaw.
- *2. Load prepreg into mold and secure mold.

*Equipotential surfaces may be obtained by placing a wire mesh, or a thin resistive prepreg into mold. Another possible method is a photo-developing process similar to that used to manufacture printed circuit boards.

3. Place in oven and cure.
4. Cool down and remove part.
5. Bake out bobbin (optional).

10.1.5 Mold Comparison

Obviously, each type of mold has distinct advantages and disadvantages. General comparisons can only be made until extensive testing and design criteria become available. The reason for this is that the bobbin substrate is anisotropic in three-dimensions as a result of any of the molding processes. However, mold and equipment costs can be compared; mechanical and electrical properties may be spoken of in a general sense.

The transfer mold produces anisotropic parts since fibrous fillers will tend to be aligned along the direction of flow with increased randomness in orientation away from this line. The cavity boundaries introduce localized stress concentrations depending also upon where the point of injection is located. The resin content is usually high relative to the other processes.

In the transfer mold, the resin sweeps the surface rapidly and even though some of the air is soluble, if it cannot escape the mold, the air will just be compressed and voids in the resin will result. The resin content in relation to the amount of reinforcement should be minimized in order to improve the overall strength of the bobbins and reduce the likelihood for voids.

In the expansion mold and vacuum/pressure casting mold, fiberglass or reinforcement fabric is stacked in layers to produce the ends of the bobbin. There is more resin content between layers of prepreg than along the plane of the woven reinforcement. The filler is stuffed around the mandrel. Resin content is therefore higher in this area.

Bobbins from each mold process may readily be coated to provide the equipotential surfaces. If this is unacceptable the wire mesh potting or EMI shielding embedment methods may be used. In order to compare molds, Table 10-2 has been compiled.

TABLE 10-2. COMPARISON OF MOLDS

Mold Type	Process Compatibility ¹				Yield ²	Tooling Cost	Supplementary Process ³ Equipment Needed	Overall ⁴ Properties		Finishing Cost
	mc	hrc	wmp	emi				Elcc	Mech	
Transfer	g	g	f ⁵	f	H ~ VH	H	H	g	f	L
Press. Cast	g	g	p	.	L	L	M ~ H	f	f	L ~ M
Expansion	g	g	p	p ⁶	M	L ~ M	L	g	g	L

Abbrev: g, f, p = good, fair, poor, respectively
 VH, H, M, L = very high, high, medium, low, respectively
 mc = metallic coating
 hrc = high resistance coating
 wmp = wire mesh potting
 emi = EMI shielding plastic embedment

¹ The ability of the various molds to form bobbins consisting of the various equipotential surface types. Rated according to ease of fabrication.

² The transfer mold has a very high potential yield, but the actual yield will depend on the tool design as well as the method of fabricating the equipotential surface.

³ This is the cost of equipment used in conjunction with the mold including ovens, pressure chambers, etc. The pressure casting mold equipment costs can vary greatly. A more elaborate system is a programmable chamber which will cycle between vacuum and pressure while curing the resin system.

⁴ Based on allowed methods of reinforcement, allowable densities and minimum resin conditions. A rating of "fair" is still considered to be adequate.

⁵ The mesh size and wire diameter must be compatible with the mold pressure.

⁶ EMI plastic is in the form of a sheet which makes up part of the laminate. Unless supplied from the vendor in exactly the right shape, the sheet must be formed and installed by hand.

10.1.6 Comparison and Development of the Coating Method

In order to examine the vacuum/pressure casting process and the feasibility of producing bobbins with equipotential surfaces, parts were made and studied as shown in Table 10-3.

10.1.6.1 Process Development

The three bobbins which were made without the equipotential surfaces were visually examined for voids and cracking. Although no voids in the resin were observed, cracking in two of the bobbins was found along the mandrel where more resin is present. It was determined that the bobbins were cracked upon removal from the mold. The process for making additional bobbins was developed by using more fiberglass around the mandrel in the mold. Also, the second mold for the conventional bobbin (Figure 10-7) facilitated part removal by allowing the mandrel to be disassembled from the mold first.

TABLE 10-3. COMPARISON OF COATING METHODS

Qty (ID Number)	Bobbins		Equipotential Surfaces			Overcoating		Surface Connections		
	Type	Substrate	Material	Process	Type	Qty	Material	Qty	Type	Method
3 (1-3)	Conv	Epon 825 HV, fiberglass, polyester mat	None	-	-	-	N/A	-	-	N/A
5 (4-8)	Conv	Epon 825 HV, fiberglass, polyester mat	Aluminum	Vacuum deposition coat	LR	2	Parylene, 1.1 mils	1	Wire	CSB
						3	Chemglaze Z051, clear polyurethane, 1 mil	4		N/C
12 (9-21)	Conv	Epon 825 HV, fiberglass, polyester mat	Chemglaze Z051, plus 5.35% by wt carbon black	Spray coat	HR	5	None	-	-	N/C
						3	Chemglaze Z051, clear, 0.5 mil	3	Term.	CFB
						5*	Chemglaze Z051, clear, 0.8 mil	5	Wire	CSB
1 (22)	L	Epon 825 HV, polyester mat	Same as above	Spray coat	HR	1	Chemglaze Z051, clear, 1 mil	1	Term. and wire	1/
Abbrev: LR = Low resistance (less than $10^7 \Omega/\text{sq}$) HR = High resistance (greater than $10^7 \Omega/\text{sq}$ but less than $10^9 \Omega/\text{sq}$) Conv = Conventional Term. = Terminal CSB = Conductive Spot Bond CFB = Conductive Fillet Bond *Part Nos. 17 and 18 have gradient control wires installed along all edges. Part No. 20 has wires installed along outer edges only. 1/ Terminals were placed through teflon inserts. (Connections to surfaces were accomplished by soldering a No. 36 wire to each terminal and conductive coating the other end to each surface.)										

Lifting of the coating along the edges of the bobbin faces was observed on three of the five aluminum coated parts. This was caused by excessive handling. Since these bobbins did not have rounded edges, the coating is more susceptible to lifting. The mold for the bobbin shown in Figure 10-4 was made with all edges rounded to help eliminate this problem. If rounded edges cannot be incorporated in the design, the aluminum coating can be recessed back from the edges. This would add complexity and time to the masking operation.

10.1.6.2 Process Comparisons

Aluminum was chosen as the deposition metal because of its thermal compatibility with the Epon 825/HV semi-rigid epoxy substrate. The

processing sequence along with the approximate time to complete each step (one bobbin only) is listed below:

<u>Step</u>	<u>Time (min)</u>
1. * Clean and dry	10
2. * Mask	60
3. Undercoat (optional) ¹	21 (hrs)
a. * Spray	
b. Cure 75°C	
c. Room temp air dry	
d. Post bakeout	
4. VD Coat	225
a. Pumpdown (5 microns, max)	
b. Plasma clean (optional)	
c. Ionization warmup	
d. Coat	
e. Set time	
5. * Clean and dry	10
6. * Overcoat ²	60 to 150
Total process time:	27.1 to 28.6 hours
Total handling time:	2.2 hours

Although Chemglaze Z001 is preferred, Chemglaze Z051 was chosen for its ease of application, good overall properties, and availability. The fabrication procedure used to apply the spray coating is as follows (time increments represent one bobbin only):

<u>Step</u>	<u>Time (min)</u>
1. Clean and dry	10
2. Mask	15

¹ Provides smooth shiny surface but may defeat the purpose of using thin aluminum vacuum deposition coating.

* Denotes operation where part must be handled.

² Electrical testing may be required prior to overcoating.

<u>Step</u>	<u>Time (min)</u>
3. Spray	144
a. Weigh out required amount of carbon black (5.35 percent by weight)	
b. Mix into Chemglaze Z051 ¹ (after adding small amount of thinner) by high speed stirring.	
c. Load air brush and spray	
d. Bake in 160°F oven for ² 2 hours	
4. Overcoat ³	132
Total handling time:	1 hour
Total process time:	5 hours

10.1.6.3 Aluminum Coating Method

No difficulties were encountered in fabricating the aluminum coated bobbins except during the masking operation. This operation was tedious since in addition to masking the edges, a narrow strip of tape must be present across each equipotential surface (see Figure 10-8) to obtain a discontinuity in the coating. This is necessary for low resistance coatings which would have a shorted turn effect.

The aluminum coating (or metallic coating) method offers certain advantages over the spray paint process. These advantages become more important as the bobbin size is reduced. Excellent coverage and thickness control can be obtained. Extremely thin coatings (4,000 to 5,000 Angstroms) will enable the designer to maximize the insulation thickness between surfaces thereby reducing the likelihood of voltage breakdown. Except for the masking procedure, relative to the wire mesh and EMI plastic embedment

¹ Chemglaze Z001 is preferred because it is more flexible than the Z051 resin system.

² Additional coats may be applied after air drying at room temperature for approximately 1 minute according to the supplier.

³ Electrical testing may be required prior to overcoating.

methods, the process for fabricating the aluminum shields is straightforward and uncomplicated. However, the overall mechanical properties of this coating (e.g., adhesion to substrate, abrasion resistance) are not as good as the properties obtained from spraying on a compatible paint coating.

On one bobbin, a No. 36 gauge wire was added to each edge of the aluminum coating by conductive staking. This was cumbersome. Alternately, this bobbin could be made by embedding the fine wires in the substrate prior to aluminum coating by using a mold similar to that shown in Figure 10-4. This is an improvement but is not ideal since the wires must still be placed into the mold.

10.1.6.5 High Resistance Paint Method

Much emphasis was placed on the high resistance paint technique for obtaining equipotential surface because of the overall ease of application (made possible by the reduced masking time) and the reduced cure to handling time (made possible by the Chemglaze Z051 system). It was found that good thickness control and coverage can be obtained on miniature bobbins by an experienced coater and good spraying technique. Measurements show that the thickness tolerance on the bobbin after spraying consistently held to better than 0.25 mil. Of the fourteen bobbins spray coated, no problems were encountered in the fabrication process.

Chemglaze Z051 is a clear, moisture curing polyurethane produced by Hughson Chemical Co. for use on semi-flexible or rigid substrates, reference 16.2.6. It can easily be made conductive by milling or stirring into the resin an amount of conductive filler. Since a high resistance coating is desired (about 10^8 ohms/sq) a small amount of carbon black was stirred into the resin. Chemglaze Z001 is also suitable for spray coating. It is more flexible than Z051 and will withstand greater temperature extremes, but this material was not available in time for this investigation.

Both materials are desirable for the following reasons:

1. Ease of application — one component system; requires little or no thinning to spray.
2. Cure rate can be controlled — choice of slow, medium or fast catalysts at various concentrations. Material will dry hard in five minutes using the fast catalyst according to the supplier.

3. Easily made conductive and is easily overcoated.
4. Approved by NASA for low outgassing space use.
5. Excellent overall mechanical and electrical properties - good abrasion, impact, chemical and solvent resistance. High dielectric strength of 3800 volts per mil, reported by supplier.

10.1.7 Terminal Installation and Interfacing

Terminals were primarily installed to facilitate electrical testing of the coating themselves but some consideration was given to the electrical and mechanical reliability of the terminals. A detailed process for interfacing with the equipotential surfaces was beyond the scope of this investigation; however, connecting the terminals to the coatings was accomplished using two different methods.

10.1.7.1 Conductive Fillet Bonding Approach

A bobbin with terminals conductively bonded to the shielded surfaces, demonstrates the first method (see Figure 10-9). The terminal passes through both surfaces but is conductive filleted to only one of the surfaces using a silver filled epoxy. Continuity is not made to the other surface since an area around the terminal was removed by masking with dot tape prior to spraying. After close examination of these bobbins, the process was considered to be inadequate for electrical interfacing on high voltage parts unless:

1. Some consideration is made to reduce the electric field gradient between the coating edge and terminal such as by placing a fine wire around the edge of the mask dot area.
2. Conductive bridging can be avoided between the coating and terminal after the filleting processing.
3. The filleting takes place inside the face of the bobbin using a concave recess.

The above changes are not complete but indicate needed improvements. Corona and other electrical tests would be needed to examine the conductive filleting process after making the necessary improvements. The exact causes of breakdown would have to be pinpointed. This method of terminal installation was not considered further in this investigation.

10.1.7.2 L-Bobbin Approach

An alternative approach is shown in Figure 10-6. Here, the wires along the edges of the coating were soldered to the terminals. Hence electrical continuity was not relied upon by an adhesive spot bond. Since tooling was not available the wires were placed along the bobbin edges by staking, prior to coating. The terminals are seated in teflon inserts which fit in holes in the non-coated portion. One teflon insert has a small hole in it to allow the fine wire to pass through. The feedthrough portion of the terminals can be potted along with the inductor itself. Improvements in this method include the following:

1. Terminals may be potted directly into the bobbin eliminating the need for teflon inserts.
2. The fine wires along the bobbin edges may be embedded into the part using the proper tooling (Figure 10-4, sheet 2). This would eliminate the wire staking operation.
3. Masking refinements would be needed to avoid electrical shorting resulting from overspray.

10.1.7.3 L-Bobbin Fabrication

The preferred process for fabricating the bobbin shown in Figure 10 is listed below. It is compared with the method actually used, since tooling which took into account the fine wires around the edges was not available:

<u>Step</u>	<u>Preferred</u>	<u>Actual</u>
1	Fabricate L-bobbin with terminals including embedment of wires (or alternate method of gradient control) along the outside edges.	Fabricate L-bobbin and provide holes for terminals.
2	Mask bobbin, terminals and ends of terminal wires.	Stake wires along bobbin edge. Install teflon inserts and terminals.
3	Spray high resistance coating and cure.	Mask bobbin, terminals and ends of terminal wires.

<u>Step</u>	<u>Preferred</u>	<u>Actual</u>
4	Route wires and solder to terminals.	Spray high resistance coating and cure.
5	Electrical test and overcoat.	Route wires and solder to terminals.
6	Encapsulate terminal connections.	Electrical test and overcoat.
7	-	Encapsulate terminal connections.

NOTE

Actual design is more complex in that three terminals are necessary. The third terminal is electrically insulated from both equipotential surfaces.

10.1.8 Testing

10.1.8.1 Prior to Overcoating

Electrical testing of the bobbins prior to overcoating was straightforward. The bobbins were first tested for shorts between the two equipotential surfaces by measuring the resistance while applying up to 1000 vdc. Higher applied voltages will be necessary for testing of advanced high voltage bobbins where terminal interfacing and surface edge problems have been worked out in greater detail.

10.1.8.2 Resistivity of High Resistance Coating

A test coupon was prepared along with the spray coated bobbin in order to verify the surface resistivity of the coating. A resistivity value in the 10 to 100 megohm per square range was considered adequate.

Little or no work has been done concerning the filling of Chemglaze Z051 to obtain high resistance values for thin coatings. The following selected resistance measurements were obtained at 1 ± 0.1 mils. (See Table 10-4.)

TABLE 10-4. RESISTIVITY VERSUS PERCENT
CARBON BLACK FILLER

ID	Percent Filler Carbon Black	Surface Resistivity Megohms/sq*
1	25	0.0003
2	15	0.00065
3	8	0.05
4	6	1.2
5	5.5	2.0
6	5.4	75
7	5.35	110
8	5.0	2500

*Test voltage = 100

10.1.8.3 Insulation Resistance and Corona Discharge

The insulation resistance values shown in the following table were taken between the two equipotential surfaces. The connection to each surface was provided by terminals or wires. The corona discharge results are also shown.

TABLE 10-5. INSULATION RESISTANCE MEASUREMENTS

Bobbin Number (See Table 10-1)	Connection Type	Resistance (Teraohms)			Corona ^{2/} Discharge Level (kilovolts)	
		100 volts	500 volts	1000 volts	CIV	2pC
15 ^{1/}	Terminal	0.015	0.075	0.033	1.55	2.40
16 ^{1/}	Terminal	0.11	0.055	0.023	1.33	1.40
17	Wire	1.0	0.73	0.33		
18	Wire	1.2	0.90	0.40		
19	Wire	1.0	0.76	0.70		
20	Wire	2.1	1.2	0.90		
21 ^{1/}	Wire	7.0	0.040	0.037		
22	Wire/Terminal	2.3	2.1	1.95	1.57	1.92

^{1/} Bobbin was determined to contain minute cracks in the insulation before coating.
^{2/} CIV = corona inception voltage under freon
2pC = two picocoulomb pulse inception voltage

10.1.9 Conclusions

10.1.9.1 Process Control of Shielding Surface Fabrication

When controlled depth embedment is not required, the high resistance coating and the aluminum coating method for obtaining equipotential surfaces seems reliable. Difficulties will be encountered using the Chemglaze system if the conductivity of the high resistance coating must be limited to a narrow range. Even though the filler was weighed on an analytical balance, at 5.35 percent carbon black by weight, the resistivity results varied by about 35 percent on three specimens. The thickness variance of the test coupons (1.0 ± 0.1 mils) also contributed to this error. For the vacuum deposition method, difficulties will be experienced in trying to obtain accurate dimensional control of the break across the coating; especially when using the masking tape method.

10.1.9.2 Proposed Further Work

There are many possibilities for future developmental work for fabricating the modified bobbins not included in this investigation. The suggestions below represent some of these possibilities:

1. Plating method - Certain plastics may readily be plated.
2. Controlled high resistance spraying - Parts may be rotated and automatically sprayed in order to more accurately control the surface resistivity.
3. Alternate masking method for obtaining break in aluminum coating (e.g., wire masking, controlled scratching of the aluminized surface).
4. Photographic/etching process for obtaining desired surface contour on bobbins.

Possibilities which have been explored but require further work are:

1. Thermal expansion mold - design and make bobbins to determine feasibility.
2. Interconnection to equipotential surfaces.
3. Design two step transfer mold or family plunger mold to obtain EMI plastic shielded bobbins.

4. Methods for obtaining gradient control of equipotential surfaces edges other than wires.

10.2 THERMOPLASTIC AND THERMOSETTING PLASTICS FOR COIL SUPPORTS

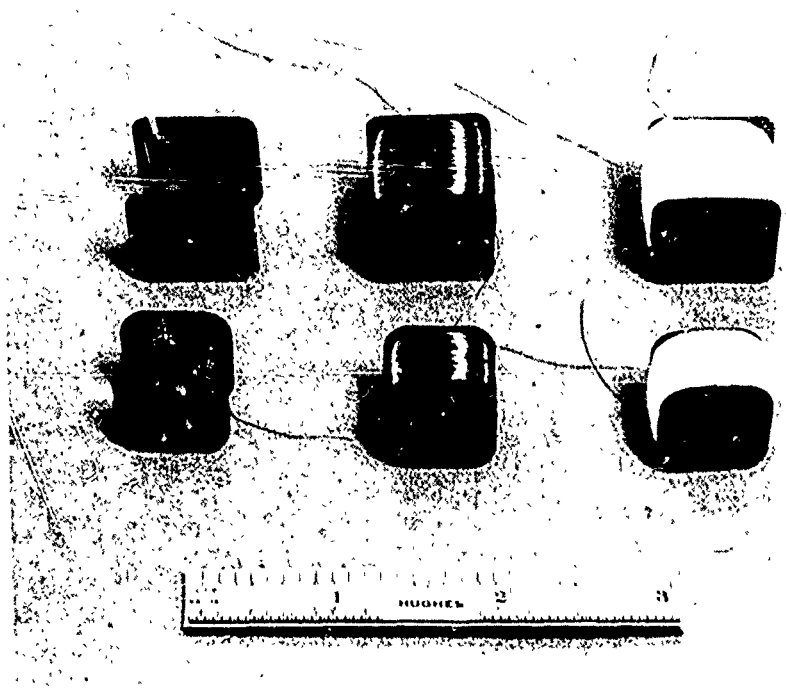
It should be obvious that, with properly designed molds, thermosetting plastic materials can be used for coil supports, i. e., bobbins, and such materials and processes are covered rather extensively in previous sections of this report. On the other hand, the use of thermoplastic materials for coil supports in high reliability components which are subjected to high temperatures either during operation and/or during the testing phases has not been approved due to the very nature of these materials, that of softening under high temperatures. Even though the bobbin may be totally encapsulated, concern exists as to what would be taking place with a softening of the coil support.

Recently, however, several high temperature thermoplastic materials have become available. Four of these, polyphenylene sulfide, polyethersulfone, polyamide, and thermoplastic polyester, were investigated. Table 10-6 summarizes the qualitative characteristics of these four thermoplastics. Bobbins molded from polyphenylene sulfide under the trade name of Ryton R-8 were obtained because this material had a much higher heat deformation temperature, in excess of 500°F, than the other three materials. Other factors which favored it for selection as a possible candidate for high reliability components is low water absorption compared to the other materials. This would be important especially in high voltage applications. However, the dielectric strength is lower than the other materials but the difference is small, and a slight increase in thickness will make up for the lower value. It is interesting to note that all of these materials have a coefficient of thermal expansion much closer to copper as compared to nearly all thermosetting materials. This would reduce the stresses applied to fine wire at the higher temperatures, still below the softening point.

As shown in Figure 10-11 a single coil was wound using AWG 39 wire on the bobbins, to determine the degree of penetration and adhesion of a typical encapsulation material. Attempts to swage terminals into the bobbin to serve as supports for the coil were not successful because the material is

TABLE 10-6. QUALITATIVE COMPARISONS OF
THERMOPLASTIC RESIN SYSTEMS

Material	Polyphenylene Sulfide	Polethersulfone	Polyamide	Thermal-plastic Polyester
Trade Name	Ryton R-8	1C1200P	Thermo-comp Zytel Nylon 6/6	Valex Celanex Tenite
Shrinkage	F	F	F	G
Adhesion	F	G	P	G
Impact Resistance	P	G	E	G
Heat Distortior.	G	F	G	F
Water Absorption	G	F	P	G
Solvent Resistance	F	P	G	F
Price	Lo	Hi	Lo	Lo
<p>E - Excellent</p> <p>G - Good</p> <p>F - Fair</p> <p>P - Poor</p>				



80 9213

Figure 10-11. Single coil wound on thermoplastic bobbin.

very brittle. As an alternate approach, terminals were spot-bonded. Attempts to solder the coil wires to these terminals result in softening of the bobbin material to the extent that the terminals actually fell out. Since this was a prime constraint in the Work Statement, further evaluation of this material as a coil support in high reliability electromagnetic components was not considered to be fruitful; consequently, further investigation was dropped.

10.3 ANCHORING OF WINDINGS WITHIN TRANSFORMER COILS

Conventional methods of anchoring windings during the winding operation has structural and reliability implications which was evaluated and investigated under this task. The term "anchoring" in this context includes both the anchoring of the turns at the end of the winding pass and also the ability of the encapsulation material to flow freely and produce a void-free encapsulation throughout the winding.

Specifications for the high voltage toroidal transformers, Figure 9-6, and the high voltage biased C-core inductor permitted mylar tape to anchor the turns, and in the case of the inductor, called out the use of kraft paper. Since such paper, while good insulation in itself, is not porous to encapsulation compounds, the possibility of air entrapment or voids was prevalent. In order to update the technology of manufacture, a porous tape or fiber mat was substituted for the kraft paper of equivalent thickness and was employed in later productions of the C-core component for test and evaluation. Because of the newness of both the spot bonding and the porous tape, winding personnel required some training to familiarize themselves with the new procedure. During this investigation not enough items were fabricated to allow them to get up on the learning curve. In an actual production operation, it is felt that such would be easily done and would result in a much higher reliability component for missile system applications.

Anchoring of the turns at the beginning and ends of a winding pass will be considered first, followed by the anchoring of the winding themselves by the encapsulation material.

10.3.1 Anchoring of Turns

The conventional use of mylar tape by winding personnel, while fast and convenient, introduces some unrealized and unrecognized problems in coil windings. Using this tape to anchor turns of a winding introduces a possibility of entrapping air or enclosing a void, due to its lack of porosity making it impervious to encapsulation materials. Also, with some resin systems, it is possible that the adhesive on the mylar tape may inhibit curing in that region. A corner or edge of the tape which happens to protrude into the encapsulation creates a concentrated stress region capable of initiating cracking. This is very obvious in transparent materials, and it is logical to believe, occurs also in opaque materials.

In the case of insulation between winding layers or between different windings, the conventional practice is to use a mylar tape because of its very excellent voltage breakdown ratings. However, this is offset by the probability that air will be trapped because of the inability of the encapsulation compound to penetrate through the tape; consequently, to obtain a higher reliability, high voltage components, it is more important to ensure that a void-free monolithic encapsulation of the winding is achieved. This can be achieved only if the tape used to insulate between windings is porous and allows the encapsulation to flow freely throughout and eliminate all voids.

A substitution of quick-setting adhesive materials for the mylar tape for anchoring the ends of the winding passes so that the outermost coils would not collapse or slip down into cavities due to the pressure of the subsequent layers will be covered in this section.

10.3.1.1 Toroid

Usually the toroidal core is lap wound with a mylar tape to provide a cushioning effect for the first layer wound on the core. Unless the core itself is grounded any trapped air or voids under the tape would have no effect on the high voltage capability of the transformer. At the start of the winding, instead of using a small piece of mylar tape, put a small dot of adhesive on the wire and allow it to cure. Once that occurs then the

winding can proceed until the end of that winding is reached, whereupon another spot of adhesive is used. Obviously, in the case of taps the wire can be pulled out, twisted, and anchored before proceeding.

When the first winding pass is completed then porous tape should be wound over the winding to provide the required insulation for the next layer. A spot of adhesive is continued to be used to anchor the start and finish of each winding. Upon completion of all of the windings in the toroid, two layers of porous tape are wound on the outside covering all of the windings. Instead of anchoring this porous tape with mylar tape, the adhesive is used. The usual "belly band" layer of mylar tape around the periphery of the toroid is also omitted. In this manner a free and unrestricted entry of the encapsulation compound is possible during conventional vacuum encapsulation procedures. This results in a monolithic, homogeneous, void-free encapsulation.

10.3.1.2 Bobbin/Stick

Since the flanges of the bobbin are employed to prevent successive layers from falling down into previous layers, the mylar tape is usually not used in this configuration, and use of the spot adhesive is also not required. Separation of the layers of a winding, by means of a porous tape or achieving the required insulation thickness between windings, can be done.

In the case of windings on a "stick," which is similar to the bobbin with the exception that there are no flanges to retain the wires at the end of the winding pass, normal practice is to use a small piece of tape under the last few turns of the pass. The ends of the tape are folded over and trapped by the next layer as the winding begins, thus holding the last turn of the previous layer in place. Winding the layer right to the edge, then anchoring the last turn in place with a spot of adhesive, permits the next layer to be added upon after the material has set. In this manner a multilayer stick winding can be made without the use of mylar tape; however, it requires practice and experience by winding personnel to become adept at using this procedure. The spot adhesive can also be used to anchor the layers. Upon completion of the winding, two or more layers of porous tape are wound on

the outside to cover the winding and bonded in place by appropriate spots of adhesive around the edges and across the seam. The winding can then be inserted into the mold and good assurance of a void-free encapsulation be obtained.

Figure 10-12 is a section of the C-core coil wound on a stick form and using adhesive spot bonds at the end of each pass. The irregularities of the turns at the edges are due to the operator not starting precisely at the same point for each layer, not a collapsing of the turns of subsequent layers into previous layers.

In windings where intermediate leads are required the splice can be anchored with a quick-set adhesive spot on the porous fiber material, then the winding continued.

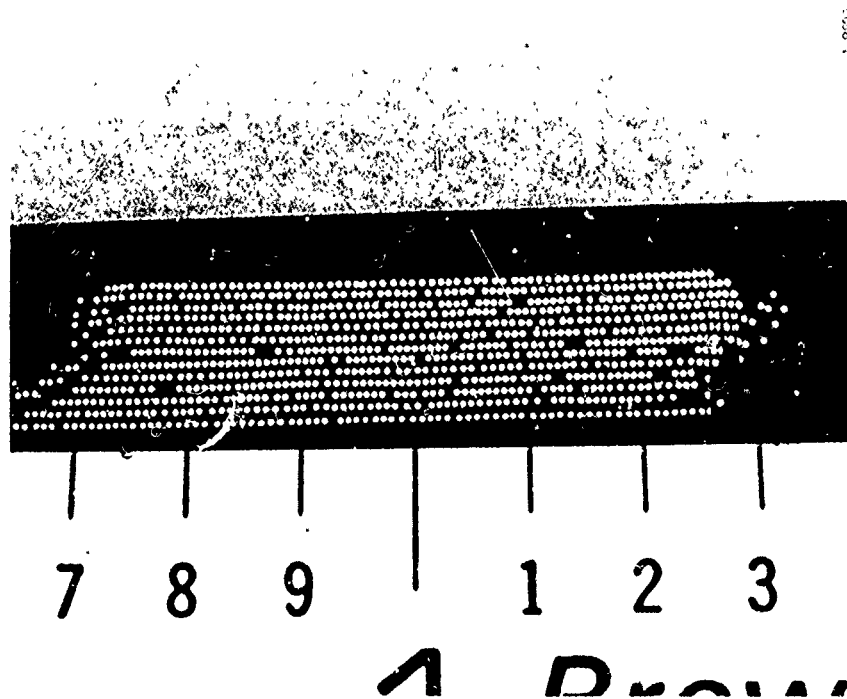


Figure 10-12. Section of the C-core coil.

10.4 C-CORE ASSEMBLY

10.4.1 Core Banding Investigation

Magnetic cores used with bobbin or stick windings are usually C-cores fabricated from prestacked, banded and cut laminations. The two halves of the smaller C-cores are usually held together by means of a metallic strap soldered under tension. This strap is installed by first bending the one end back on itself over the edge of the clip, then passing the other end around the core, through the coil assembly, and then through the clip in the opposite direction. Using a tensioning device which applies tension between the edge of the clip and the long end of the band, the band can be stressed to any given level. While in this condition, the end and the clip are all soldered together. Because of the well known characteristic of a soldered joint to "creep" and reduce the tension even at room temperatures, and the high profile of the soldered clip arrangement which becomes objectionable on small magnetic components, various other methods of anchoring the bands were investigated.

Investigation of mechanical means of securing the cores included clinching, wedging, and snap-lock approaches. The clinching approach, which is a direct application of the clinching tools used to anchor steel bands around shipping crates, overcomes the problem of solder creep but does nothing for decreasing the profile or weight of the band joint. The clinching tools available are only for the larger bands; however, smaller ones could be designed and built to anchor the small widths and thicknesses of bands used in small and miniature transformers. However, they still require a metal clip which tends to buckle under the clinching operation, increasing the profile even higher than during the soldering approach. Also the clinching deforms or even cuts into the band creating a stress point which could cause a progressive fracture and eventually the band would break under repeated stress cycling.

The use of a wedge is an additional item over the clip to wedge and serve as an anchor for the end of the band. This, again, overcomes the solder creep problem but increases the weight and profile also. The snap-lock approach, during initial investigation, appeared to have no significant advantage over any of the other mechanical approaches.

A breakthrough achieved in the welding approach overcame both of the original problems and so far overshadowed other mechanical means of securing the bands that these were discontinued from further investigation. Instead of using a clip, a pull-tab of the same material as that of the band is spot-welded or impulse-welded to the strap as shown in Figure 10-13 prior to the banding operation. The band is slid around the core and through the bobbin and the two longer ends pulled by the band tensioning equipment. When the desired tension is reached the long band overlapping the short band on the core are impulse-welded with a capacitor discharge welder, anchoring it solidly. The ends of the two bands pulled by the tensioning equipment are cut off close to the core and additional impulse welds made along to anchor the cut ends. Thus it can be seen that the maximum thickness involved is two thicknesses of the banding material, which is as thin as can possibly be obtained. No clip is required.

For the banding operation under tension, the original approach was to use a parallel gap welding configuration where both electrodes are on the same side of the material. By applying suitable pressure the current passes through both layers of the material, resulting in a fusing together of the metal. It was found, however, that this process would work very well for stainless steel bands but not for beryllium copper due to its much higher conductivity. Subsequent tests showed that the parallel configuration was not required as the ground electrode could be located elsewhere and then a single hand-held, pressure-actuated, welding electrode used to weld the

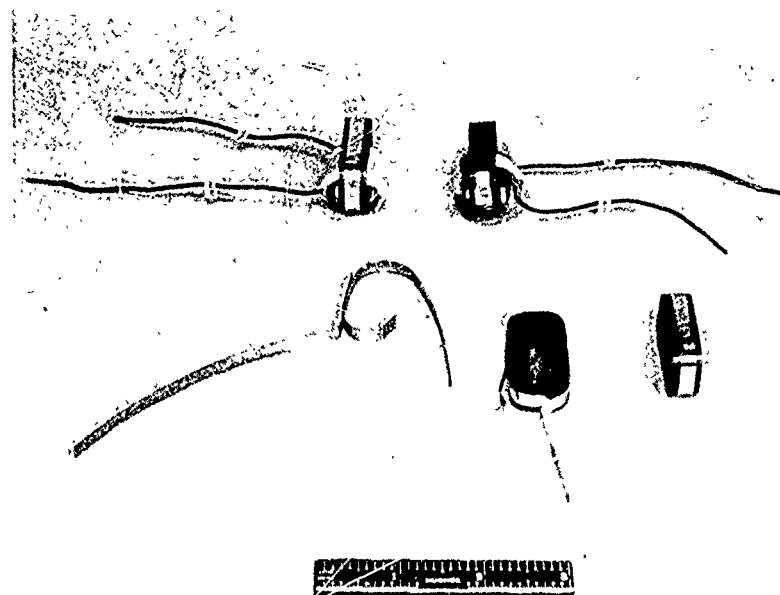


Figure 10-13. Welded core banding technique.

bands together, as shown in Figure 10-14. This approach lends itself to all sizes of bands, beryllium copper as well as steel.

10.4.2 Weld Schedule

The conventional method of obtaining a weld schedule involves the welding of a large number of samples at various energy settings and electrode firing pressure settings, then subjecting these samples to a pull test to determine their strength. This weld schedule applies really only in either parallel gap or opposed gap welding situations where spacing of electrodes is constant. Careful control of all the parameters is required for such weld schedule data to be useful. The opposed gap electrode configuration, while applicable to the welding on of the pull tab, cannot be used in the actual welding of the band on the core because, obviously, the core is in the way of the bottom electrode. Parallel gap welding, where both electrodes are on the same side, requires a fixture to back up the core to offset the electrode

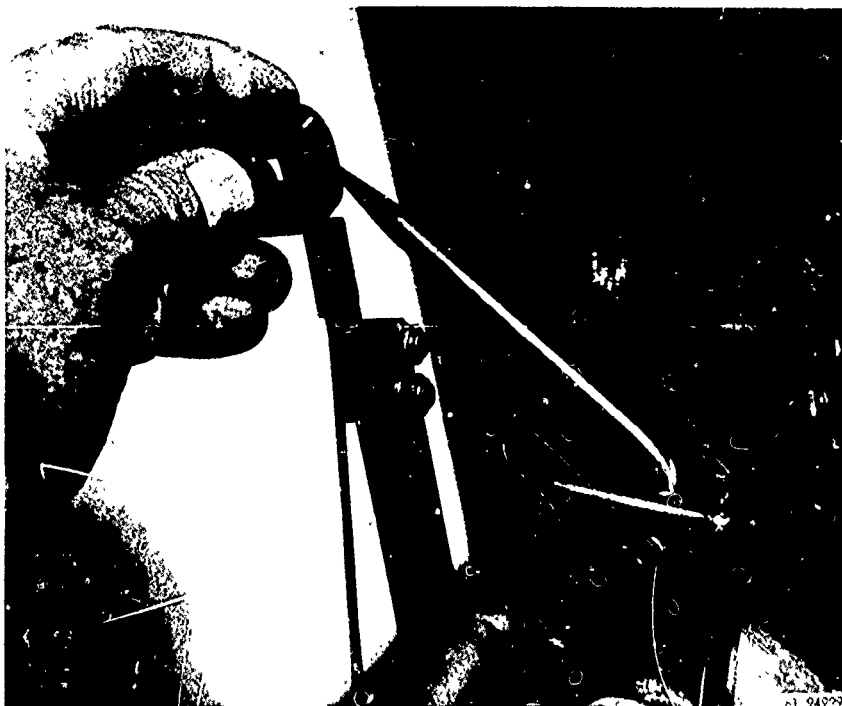


Figure 10-14. Welding of core band using single hand-held electrode.

pressure involved at the same time the bands are being put under tension by the banding equipment. Also, many times the welding occurs on the curve of the core section which would require the electrodes to be formed into that curvature if parallel gap welding was used.

For purposes of demonstration of the technique, separate electrodes were used. The ground electrode, or negative, was clamped to the banding equipment frame which provided electrical continuity through the jaws to the band under tension. The hand-held copper electrode, calibrated by means of a welding electrode pressure gauge, was set to fire the welder at 2 pounds unless otherwise designated.

The welding test data was developed for a 2 lb firing point on the hand-held and for 16 psi pressure applied to the banding equipment. Two sizes of bands were evaluated, both sheared from corrosion-resistant (CRES) steel sheet. A 5 mil by 2.0 inch wide band typically used for small cores, and a 10 mil by 3/8 inch wide band for the larger cores were the sizes evaluated.

The configuration used to obtain the weld data is shown in Figure 10-15. A continuous strip was wrapped around a core and inserted through the sliding jaws into the clamp on the banding machine. A smaller piece simulating the attachment point of the band was located underneath this long band. It can be seen that a continuous strip is used rather than welding on the pull tab so as to eliminate one possible additional parameter, that of conductivity of the weld current through the previous welds. At 16 psi air pressure applied to the banding equipment and 2 lb firing force on the hand-held electrode, two welds were made across the band as shown at approximate one-third spacings. Two welds, side by side, were used rather than one because it was found that the weld appeared very weak during any kind of rotating motion, and two would prevent this from occurring during the pull test. Welds were made at various watt/sec energy settings on the welder. After welding, the tension would be released and the welded band and short tab removed and the breaking strength of the weld determined on an Instron pull tester.

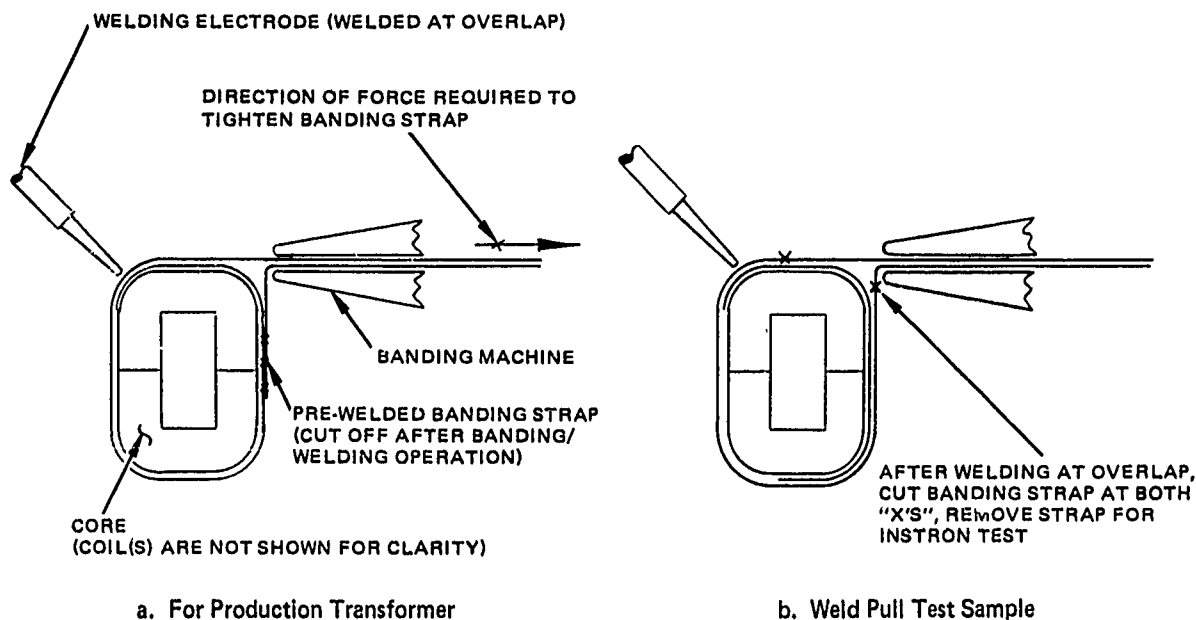


Figure 10-15. Welded band configurations for production and pull tests.

The results of the tests are plotted in Figure 10-16 showing breaking strength of the weld versus watt/sec. The initial point taken on the first run was at 75 watt/sec to check the operational system, then readings taken for every 10 watt/sec starting at 40-90 watt/sec. Plotting of this curve with the initial point at 75 showed a dip in an otherwise relatively smooth curve. Considering this to be an anomaly of the first run, the succeeding runs were started at 50 watt/sec up to 90 watt/sec for every 10 watt/sec, but a reading was also taken at 75. All showed this characteristic dip as in the first run.

The reason for this dip is not known at this time. It could be due to some eccentricity of the welder that the 75 watt/sec position actually puts out less energy into the weld than at 70 or 80 watt/sec. It was also possible that this happens to hit upon a combination of pressure and resulting weld temperature which weakens the weld at that one setting. Further work needs to be done to ascertain the cause. Until this anomaly is understood, precise

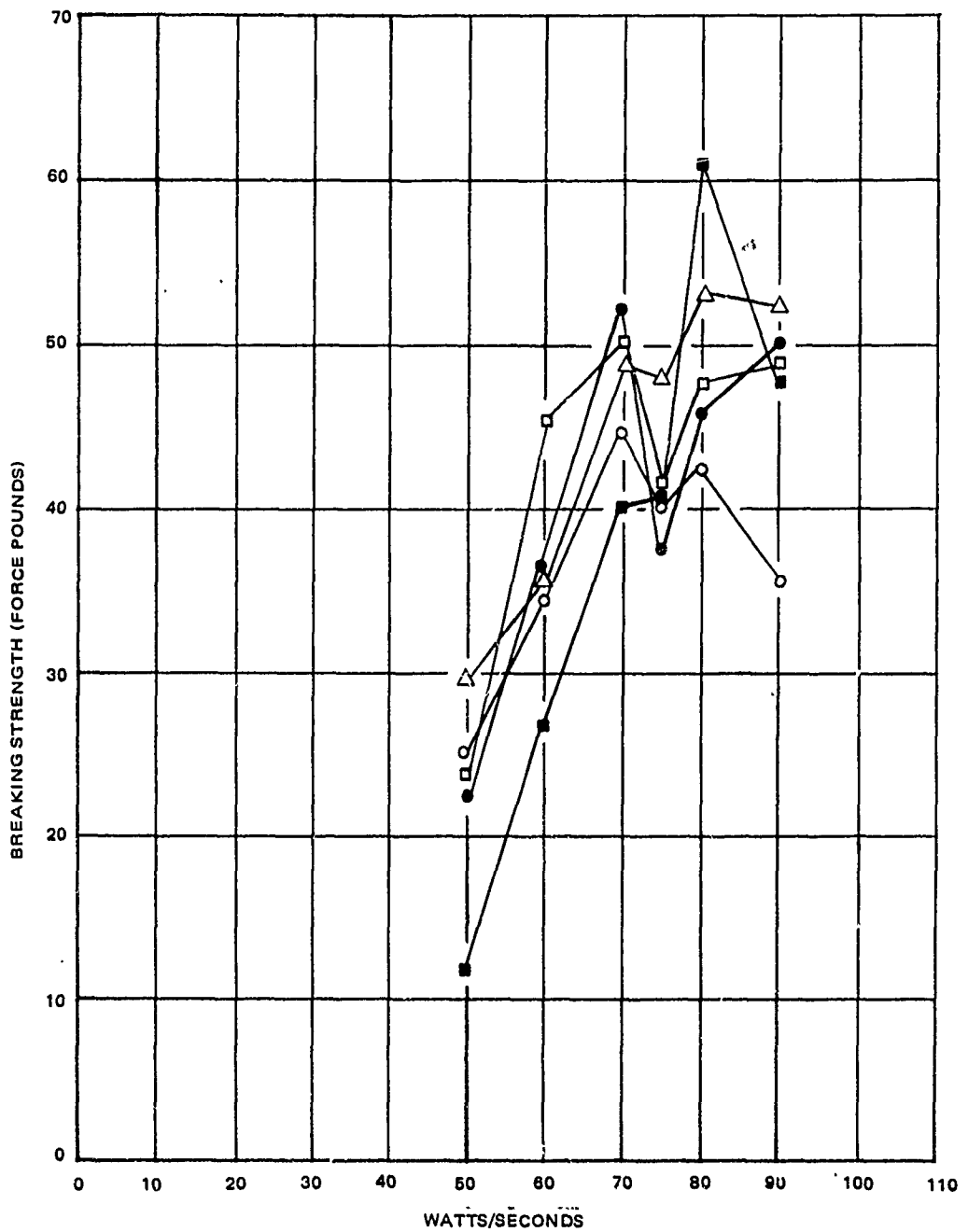


Figure 10-16. Weld breaking strength versus welder energy for 5 mil x 0.20 in. CRES for 5 samples, 2 welds/sample.

setting of the welder to obtain the maximum breaking strength is somewhat questionable. However, realistically, even the lowest point at 75 watt/sec has a large percent breaking strength compared to the ultimate strength of the strap.

To give a comparison of the breaking strength of the welds with regards to the ultimate strength of the strap of the 5 mil by 3/16 inch CRES, the ultimate strength was calculated by multiplying the cross-sectional area of $9.4 \times 10^{-4} \text{ in.}^2$ times the ultimate strength of 75,000 psi results in a caculated tensile strength of 70 pounds. At the worst case, at 75 watt/sec, the breaking force is still of the order of 60 percent of the strength of the strap itself, which shows that a very effective weld is obtained with the present configuration.

Weld test data for two other welding configurations were taken on the 10 mil strap, because it was too wide for the banding equipment.

The first, a parallel gap arrangement, with both electrodes held approximately 0.25 inch apart, welded two pieces of overlapped banding material. The results are shown in Figure 10-17, where it is obvious that the maximum of the curve has not been reached because of the energy limitation of the welder. Going to a grounded plate configuration for the second weld configuration, as shown in the same figure, the return is connected to an aluminum alloy plate and the welding electrode discharges across the lapped straps. At each energy setting, three welds were made. On the first sample, which, when plotted in Figure 10-17, shows a peak around 70-80 watt/sec. The second sample in this configuration had four welds at each energy setting and appears to continue rising beyond the limit of the welder, if the point at 80 watt/sec is disregarded. Again, whether this is an anomaly of the welder similar to that occurring on the thinner strap materials, is not known.

In order to implement this process into an actual production setup, it is necessary, of course, to establishe the fixture configuration and vary the various parameters to obtain the optimum weld for a given transformer configuration. Since the present MM&T program is for missile-type transformers, it was considered that further work was not necessary on the

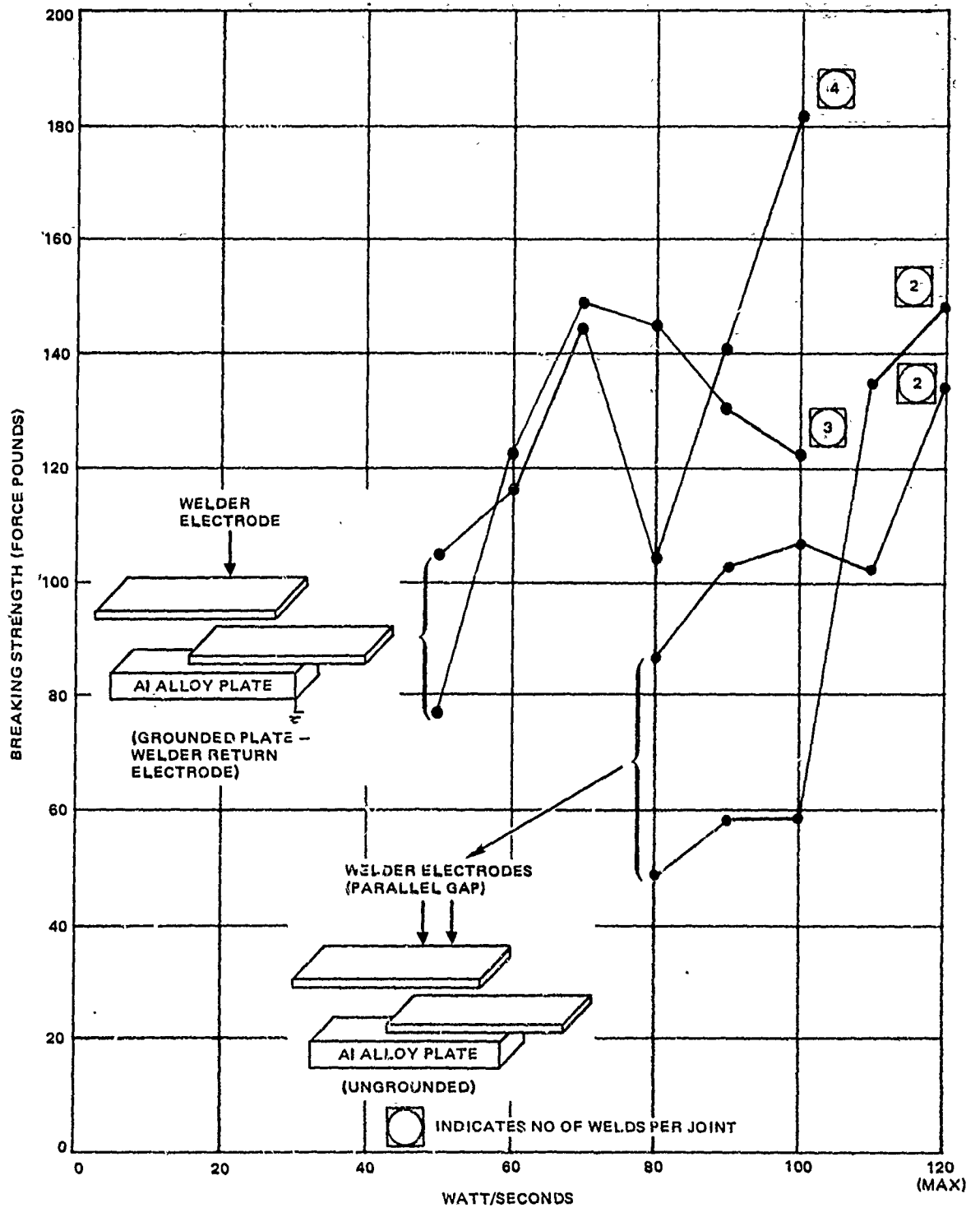


Figure 10-17. Weld breaking strength versus welder energy for 10 mil x 0.375 in CRES for 2 welder configurations.

heavier strap because transformers of this size are usually not part of a missile electronic system.

10.4.3 Temperature-Tension Tests

Soldering is the accepted method of anchoring the bands under tension on smaller cores. However, because of the well known fact that solder is very poor in shear, especially at elevated temperatures, this test was planned to compare the maintenance of tension of soldered bands versus welded bands. A Baldwin SR-4 strain gauge was bonded to each of three CRES steel straps, 5 mils by 0.24 inch wide, and to each of two tinned carbon steel straps, 6 mils nominal by 0.187 inch. Using a strain gauge bridge and the Instron, a calibration factor for the carbon steel was 1.78 pounds per millivolt, and for the CRES steel, 2.27 pounds per millivolt.

Pull tabs were welded on the three CRES bands and the band wrapped around a C-core with 20 psi on the bander and welded six places. The pull tab and the extra ends were trimmed off.

The tinned carbon steel bands were wrapped around a core and inserted through a clip and put under the same tension, being soldered in the conventional manner. The extra material was then snipped off.

Table 10-7 summarizes the tension measurements during and just after banding.

Another purpose of the test was the realization that tension applied to the CRES band by the bander as required by the spec would be appreciably less after welding because there is a section of band located between the weld tap and the end where the weld is to be made that is not stressed. When the bander is released after the weld, it is obvious that there will be some relaxation of tension. It would be of interest to be able to measure this in order to offset this condition by increasing the tension by an equivalent amount. By observing the strain gauges during the banding operations it was estimated that the relaxation of tension due to the stress being applied to the unstressed section when the bander was released was of the order of 6 to 10 percent.

TABLE 10-7. COMPARISON OF CREEP TEST VERSUS TEMPERATURE-TIME FOR SOLDERED AND WELDED BANDS

Sample No.	Strap Matl	Size	Solder/ Weld	Gauge Factor, lb/mV	Tension, lb ⁽¹⁾		
					After ⁽¹⁾ Solder/ Weld	48 hrs at ⁽⁴⁾ 102°C	168 hrs at ⁽⁴⁾ 102°C
1		6 inils/ 0.187	Solder	1.86	1.7	-5.4	-5.6
2		6 inils/ 0.187	Solder	1.78	(2)	-	-
3	CRES	5 inils/ 0.245	Weld	2.27	-0.91 ⁽³⁾	-2.9	-3.4
4	CRES	5 inils/ 0.212	Weld	2.27	8.8	3.2	5.0
5	CRES	5 inils/ 0.240	Weld	2.21	4.6	2.9	3.8

Notes: (1) Strain gauge readings questionable during soldering/welding because of error in settings of HP 42SAR DC microvoltammeter.
(2) Strain gauge lead was broken prior to banding operation; strap was removed from core.
(3) Bander did not apply rated tension to sample during banding operation for unknown reason.
(4) Temperature of samples at 48 hr reading higher than ambient, probable reason for consistently lower readings than at 168 hrs.
(5) Before and after measurements, strain gauge bridge was balanced on unstressed strain gauge, Sample (2). If zero set points varied significantly, run was repeated.

Unfortunately, during the banding operation one of the leads to the strain gauge on sample No. 1 of the soldered band was broken; consequently, no further tests were made with this band. This unstressed band was used to zero the strain gauge bridge prior to each set of readings which enabled a practical reference point to be maintained. The negative readings for sample No. 3 at the beginning indicates that for some reason tension was not applied to the band during the banding operation; for what reason is not clear at this point. The samples were placed in an oven at 100°C and the first test was up 48 hours later at that temperature. The samples were removed from the oven and allowed to cool to room temperature whereupon the readings were made. It can be seen that Sample 3 is consistent showing a negative value, in other words, the band is not under tension; in fact, a sideways motion of the core halves was possible showing that the band was not tight. A similar attempt on the other cores showed no relative motion.

It is significant to note that sample No. 1, the soldered sample, went from 1.7 pounds tension to a negative 2.8 showing that the solder has relaxed at this temperature. A similar set of readings was taken 168 hours later with essentially the same results. Welded samples showed some variations which could be ascribed to temperature differences; however, no relaxation of tension is indicated.

In summary, the tests show that the solder exposed to elevated temperatures relaxed under tension, whereas the welded bands retained their values of tension. As mentioned before, further work needs to be done to implement this method of welding bands under tension into a production operation.

11.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions reached based on the various investigations made during the phase I and phase II of this MMT program for implementation of techniques for the manufacture of low cost, highly reliable magnetic components for missile system applications are given, together with recommendations, under the five general headings of potting/encapsulation, winding techniques, interconnection techniques, tooling and equipment, and structural parts.

11.1 POTTING/ENCAPSULATION TECHNIQUES

1. A large number of materials are available and more are being invented for encapsulation/potting of magnetic components. Since many of the various parameters and properties, especially electrical and temperature, are determined by the respective vendors under different test conditions, it is difficult for the user to make an intelligent selection for a specific application involving high reliability. Many times the user must perform tests of the significant properties under the same conditions to enable a useful comparison; consequently, it is recommended that a standard set of conditions be established, e.g., voltage, temperature, frequency, sample size and configuration.
2. A major source of failure in magnetic components wound with fine wire is the leads between the windings and the terminals to the outside world. Based on information developed it is recommended that single strand lead-out wires smaller than AWG 36 not be used. Alternate methods such as twisted multiple strand self leads, reinforced multiple twisted leads, and skeining should be investigated for high reliability applications.
3. Methods of joining fine wire to intermediate leads of AWG 36 using properly designed fixtures need to be investigated thoroughly. Methods of welding, and cold joint connections need farther work.

4. Pressure sensitive magnetic cores and other fragile electronic components require low stress potting/encapsulation techniques and materials. Quantitative evaluation of techniques and materials requires a convenient, practical method for measuring stresses developed by embedment materials as a function of temperature. One method, using pressure calibrated mercurial thermometers, was demonstrated on 10 low stress materials by detecting glass transition temperatures for some, and giving a quantitative picture of the stresses generated by all over the temperature range of the thermometer. Extension of the method to small inductors with 3 types of pressure sensitive toroidal cores was partially successful, but requires additional work.
5. Concurrent with the development of pressure sensitive inductors was the observation of quantitative effects of high hydrostatic pressures on the electrical parameters of small toroidal inductors themselves. The pressure pot developed, with electrical leads available through a pipe plug interface, would enable the evaluation and comparison of many core materials.
6. Setting 200 psi maximum as the upper limit of low stress materials, the following materials qualified: Conap EN-9, Conap EN-9-0ZR, Uralane 5753, RTV-615, RTV 619, RTV 627, and RTV 655. All these has no apparent glass transition temperature down to -40°F , according to thermometer data.
7. Scotchcast 255, although having a measured glass transition temperature at 95°F , reaching 1600 psi at -40°F , was selected to be the second part of a two part system selected to reduce embedment stresses. The first part consisted of RTV 619, RTV 627, or a polyethylene wax, Epolene C/AC 617. Although significantly reducing the measured stress, the 200 psi limit was far exceeded. It appears that two part systems are not the answer to low stress embedment techniques because the first stage soft materials are really not compressible when totally enclosed. It is proposed that a first stage material must be porous to be really compressible. Such materials would not be acceptable for high voltage applications.
8. For high voltage applications Epon 825 with HV hardener was the only material that showed zero corona level. Scotchcast 255 and Eccoseal 1218 showed high corona levels, although their dielectric strengths were sufficient to pass short interval breakdown tests.
9. On the basis of all tests run and extensive investigations it is concluded that there is no universal ideal embedment material. Tradeoffs of parameters and properties are required for each application.

10. A total of 40 embedment materials were tested and evaluated for high reliability magnetics, which is a representative cross section of the available material types. This was done on the basis of a total of 36 parameters, 13 of which were selected as being most important.
11. Only 20 of the 40 materials were evaluated on the basis of outgassing because of lack of manufacturer's data on the remainder, or the equivalent Hughes specification.
12. A major concern in the selection of an embedment material is the ease of flash removal and cleanup, which is also governed by the type and configuration of the molds. An investigation into mold design which would overcome the cleanup problem would allow a greater selection of materials in production.

11.2 WINDING TECHNIQUES

1. Based on the results of this investigation and visits to vendors, it is recommended that all reels of magnet wire intended for high reliability magnetics be shipped, stored, and handled in accordance with "Style C" to protect the wire and its reel from damage and contamination. Style C is defined as a paper wrap around the wire, and the reel encased in a rigid foam plastic. The only time that these are to be removed from the reel is during the winding operation, and replaced when completed.
2. Precautions in using shuttle type toroid winder include a nick and burr-free shuttle ring placing a small piece of mylar tape across the shuttle ring after inserting the core but before loading the wire, loading the wire at constant tension, and maintaining this tension when loading is completed.
3. Shuttle type toroidal winders should be modified to allow the use of an electrical short detector continuously between the shuttle ring and the wire being wound on the toroid. This serves the dual purpose of detecting insulation damage during winding or faulty insulation on the wire itself.
4. The usual QA practice of approving a reel of wire for high reliability applications by inspection and analysis of a few feet from the beginning is not considered adequate. Equipment capable of continuously monitoring the insulation integrity of the wire during the winding operation is recommended. This can be easily done for shuttle type toroidal winders as noted above; other types will require some development effort.
5. Methods of wire stripping need to be investigated and improved. Presently available methods contain at least one significant drawback in each, especially in the fine/ultra fine sizes.

6. Insulation and even conductor deformation may occur when fine wire is wound at rated tension on square bobbins, due to the buildup at the corners. It is recommended that round rather than square bobbins be used; otherwise some wire damage may occur in the winding operation.

11.3 INTERCONNECTION TECHNIQUES

1. Investigation of wire stripping technique shows that no method of insulation removal from magnet wire, especially in the fine/ultrafine gauges, has a clear cut advantage over the others, especially for high temperature polyimide (ml) materials.
2. Insulation removal with the CO₂ laser showed promise with the larger wire sizes, but further work is required for application to fine wire gauges in a production environment.
3. Removal of insulation by abrasive particles driven by an air blast was effective for the larger wire sizes, but further work needs to be done in nozzle design and abrasive materials to obtain a clean, solderable surface.
4. Wire sizes smaller than AWG 36 should be joined to intermediate leads AWG 36 or larger, then taped or anchored to the winding, so that the intermediate lead interfaces with terminals for connection to the outside world.
5. Careful control of soldering parameters using conventional tin-lead solder produced the most reliable joints between copper intermediate leads and fine wire gauges, when compared with all other methods of joining.
6. Reduction of voltage gradients in encapsulation compounds by conductor placement, solder balling, conductive shields, radii selection, and interface geometries will reduce possibility of long-term degradation of insulation integrity in high voltage components.

11.4 TOOLING AND EQUIPMENT

1. Individual molds, designed as a pressure vessel up to 500 psi, can accommodate both pouring in vacuum and cure of encapsulant under pressure for low production quantities.
2. Slush molds and molds fabricated from RTV silicone rubber can be used for low production quantity if they are poured in a vacuum chamber and cured in a pressure vessel at 500 psi.
3. As an alternative to the pressure vessel, the silicone molds, after pouring in vacuum, may be centrifuged for 5 to 10 minutes to remove the trapped air, then cured in an oven.

4. Use of the centrifuge, instead of the pressure chamber, appeared to obtain an equally void free encapsulation of low voltage components; the CIV for high voltage components was higher for the pressure cured samples than the centrifuged ones.
5. Various sizes of automatic metering and mixing equipment, which automatically mix the resin and hardener on demand, are available to accommodate any production rate.
6. Liquid injection molding (LIM) techniques show promise for large production quantities with proper mold design and selection of materials.
7. Decreases in the cure time or "green strength" time of encapsulation materials, when the encapsulated component may be removed from the mold for a post-cure, will increase the production rate and decrease the cost correspondingly.

11.5 STRUCTURAL PARTS

1. Electrostatic shields sprayed on bobbin surfaces after molding enable better process control with less problems than integral shields positioned in the mold cavity prior to molding.
2. A high resistance coating for bobbin shields can be employed without requiring a gap, which is necessary for low resistance materials because of the shorted turn effect.
3. High temperature thermoplastic bobbin materials were not considered acceptable for high rel components because of brittleness, and softening of the region around the swaged or bonded terminals during soldering.
4. Anchoring of wires during winding operations with quick-set adhesive rather than mylar tape facilitates void free encapsulation.
5. Welding rather than soldering straps during C-core banding operations eliminates solder creep problems.

12.0 IMPLEMENTATION

The implementation requirements included the dissemination of information on an "as you go" basis during the contract period, rather than waiting for completion of the MM&T program. In this manner it was hoped that information could be put to use sooner in the manufacture of high reliability missile magnetic components. Although the MM&T program is expressly for the manufacturing operation, some of the information uncovered to improve reliability applies to the design phase; these items will be passed along as well. The implementation phase comprised both Hughes in-house operations and outside vendors, presentation of three papers at appropriate technical seminars, and a government/industry debriefing. A detailed implementation plan will be submitted by Hughes under separate cover.

12.1 OUTSIDE VENDORS

During the MM&T program several representative magnetics manufacturers were contacted and a presentation of the available information to date made to some of them. Others provided valuable information in the MM&T investigations. These are listed in Appendix 16.1. All expressed a desire to be kept informed regarding new developments, and be placed on the mailing list for both the final report and the government/industry debriefing. Contacts also gave feedback to Hughes as to what they considered were major problems in the production of high reliability magnetics.

As a part of the information dissemination phase of implementation, three papers were presented at technical symposiums. The first, "Wire deformation in Ultra-fine Wire Coils," Appendix 6.1, was presented at the

Electrical/Electronics Insulation Conference held at Boston in October 1979. There was quite a bit of interest expressed by those present, and further contacts took place afterwards. Two papers, "Low Stress Potting for Stress Sensitive Magnetic Cores" Appendix 6.2 and "High Reliability Potting Materials for Use in Missile Systems," Appendix 6.3 were given at Coil Winding Chicago '80 Symposium at Chicago, 29 September 1980. Several companies and organizations requested afterwards to be placed on the mailing list for the final report and debriefing.

12.2 HUGHES IN-HOUSE

Various Hughes in-house magnetics manufacturing facilities were contacted, and copies of the three reports, prepared during the basic phase, were sent out to each. Later, a meeting was called, on 2 June 1980 for representatives of Hughes transformer manufacturing facilities, who were given the information to date.

Implementing the findings of the MM&T program into Hughes operations is being done by revising appropriate specification requirements which then can be invoked into new programs.

12.3 GOVERNMENT/INDUSTRY DEBRIEFING

Part of the implementation effort at the end of Option 1 was the holding of a government/industry debriefing on 28 October 1980 at Hughes Aircraft Company, Culver City. The purpose of the meeting was to give to all attendees an overview of the information assembled during the two-year program, note the major findings, point out possible breakthroughs in reliability improvement, and review possible new technologies. It was hoped that this presentation would encourage those attending to delve into this final report for the complete story to take back to their organizations, with the intent of implementing appropriate bits of this technology into their operation so that higher reliability, lower cost electronic components for missile systems, space projects, and commercial applications would be forthcoming in the immediate future. If this is done effectively, a quantum jump in component reliability and cost reduction would be obtained which would benefit all concerned.

The agenda for this meeting is shown in Figure 12-1.

Over 250 invitations were sent out to government agencies and industrial organizations concerned with the manufacture of high reliability electromagnetic components. Nearly 70 attended, representing 32 organizations. Table 12-1 lists the companies and government organizations represented. The attendees were told that they would be on the mailing list for the MM&T final report consisting of volumes I and II when it was published subsequent to the debriefing additional requests for this report have been received.

Hughes Aircraft Company Technical Team:

Mr. L. Brian Keller, Assistant Manager, Technology Support Division, Electro-Optical & Data Systems Group	0830	Arrival (Building 1, Lobby)	L.B. Keller
	0900	Welcome (Building 6, Room D1111)	
Mr. Earle R. Bunker, Senior Staff Engineer, Components Development Department, Technology Support Division, EDSG	0905	Introductions	D.B. Hartman
	0910	Implementation - The Payoff	MICOM
Mr. James R. Arnett, Member of Technical Staff, Product Engineering Section, Components Development Department, Technology Support Division, EDSG	0930	Program Overview	E.R. Bunker
	0945	The High Reliability Transformer/ Inductor - Design, Wire Handling & Winding	E.R. Bunker
Mr. Bernard A. Birnbaum, Senior Associate Engineer, Electronics Assembly Section, Materials & Processes Engineering Department, Technology Support Division, EDSG	1015	Break	
	1030	Encapsulation Material Selection Problem - Parameters & Procedures	J.R. Arnett
Mr. Ronald L. Brookshire, Group Head, Metallurgy & Metal Finishes, Dielectric & Metallurgy Section, Materials & Processes Engineering Department, Technology Support Division, EDSG	1100	Interconnection & Structural Parts Investigation. Finer/ Ultrafine Wire Problems	E.R. Bunker
Mr. Kurt Carlson, Member of Technical Staff, Dielectrics & Metallurgy Section, Materials & Processes Engineering Department, Technology Support Division, EDSG	1130	Various Methods of Transformer/ Inductor Encapsulation & Projected Production Considerations	W.H. Fossey
	1200	Lunch	
Mr. William H. Fossey, Group Head, Advanced Composites Development Group, Materials Development Department, Technology Support Division, EDSG	1300	Cost Analysis & Implementation Aspects	
Mr. King H. Li, Member of Technical Staff, Product Engineering Section, Components Development Department, Technology Support Division, EDSG	1315	Demonstrations in Laboratories 1. Liquid Injection Molding (LIM) Process (Building 32) 2. C-Core Banding (Building 21) 3. Toroidal Winder With Short Detector (Building 21) 4. Low & Medium Production Encapsulation (Building 21)	
Mr. Yoshi Noriaki, Staff Engineer, Materials & Processes Engineering Department, Technology Support Division, EDSG			
Mr. D. Pat Salisbury, Member of Technical Staff, Specialty Products Group, Materials Technology Department, Technology Support Division, EDSG			
Mr. Thomas Vargyas, Member of Technical Staff, Materials & Processes Engineering Department, Technology Support Division, EDSG			

TABLE 12-1. COMPANIES AND GOVERNMENT ORGANIZATIONS
REPRESENTED AT DEBRIEFING.

S.C. Katsouleas	Sigma Power, Inc.	20790 Leapwood Avenue Carson, CA 90746
R.E. Stutz	Sprague Electric	P.O. Box 5000 Visalia, CA 93278
Phillip Brownlee	Sprague Electric	P.O. Box 5000 Visalia, CA 93278
Clarke Reise	Standard Industries	La Mirada, CA 90638
Ramesh Patel	Standard Industries	14250 Gannet Street La Mirada, CA 90638
David E. Reed	Standard Industries	14250 Gannet Street La Mirada, CA 90638
Pot Reed	Standard Industries	14250 Gannet Street La Mirada, CA 90638
John H. Eichert (for F.A. Chamberlin)	Technitrol Inc.	1952 East Allegheny Avenue Philadelphia, PA 19134
John H. Eichert	Technitrol Inc. (California Representative)	315A Del Mar Avenue P.O. Box No. 441 San Clemente, CA 92672
Ernest Gant	Tracor Incorporated	6500 Tracor Lane Austin, TX 78721
Benjamin C. Allen	TRW	One Space Park Redondo Beach, CA 90278 MS/M3-2137
Carl Holzbauer	TRW	One Space Park Redondo Beach, CA 90278
L.E. Wilson	Westinghouse Electric Corp.	P.O. Box 746 Baltimore, MD 21203
B.D. Greenawalt	Westinghouse Electric Corp.	P.O. Box 746 Baltimore, MD 21203
Bernie Weks	Zenith Transformer	Gardena, CA

(Continued next page)

(Table 12-1, continued)

Kurt R. Carlson	Hughes	Building 316, Mail Station R129 Equitable
C.A. Grimmett	Hughes	Building 316, Mail Station R127 Equitable
Floyd Hill	Hughes	Building S15, Mail Station V340 El Segundo
Vernor W. Lym	Hughes	Building 231, Mail Station 1716 Torrance
Jack Kisch	Hughes	Building 600, Mail Station F145 Fullerton
Dennis Matte	Hughes	Building 6, Mail Station C147 Culver City
Roger Allen	Hughes	Building 6, Mail Station D139 Culver City
Biu Garner	Hughes	Building 6, Mail Station D139 Culver City
Gene C. Lewis	Hughes EDD	Building 230, Mail Station 1004 Torrance
Larry Hershenson	Hughes RSG	Building S-19, Mail Station 113 El Segundo
Hoh Nu	Hughes Tucson	
Colonel McLyman	JFL	4800 Oak Grove Drive Pasadena, CA 91103
Montell Hall	Litton G&CS	5500 Canoga Woodland Hills, CA
W.I. Lewis	Magnetics	1620 Potrero S.G. Monte, CA
W.G. Salsbury	McDonnell Douglas - Department 1718	2600 North 3rd St. Charles, MO 63301
Tom LuVisi	McDonnell Douglas H.B.	5301 Bolsa Avenue Huntington Beach, CA 92647 MS 10-3
Richard Chaber	Microtran Company	Valley Stream, NY
John Wrag	OECO Corporation	23062 Andria Laguna Niguel, CA 92677
Ed Rothery	OECO Corporation	712 South East Hawthorne Portland, OR
Chris Waian	R.M. Hadley Company	750 West 51st Street Los Angeles, CA 90065
Tall Amano	R.M. Hadley Company	750 West 51st Street Los Angeles, CA 90065
Wilhelm Beer	Sigma Power, Inc.	20790 Leapwood Avenue Carson, CA 90746

(Continued next page)

(Table 12-1, concluded)

David Newton	Abbott Transistor Laboratories	Los Angeles, CA 90016
Tachio Fukuyama	Abbott Transistor Laboratories - Transformer Division	639 South Glenwood Place Burbank, CA 91506
Joe Hirota	A.M.I. Coast Magnetics	5333 West Washington Boulevard Los Angeles, CA 90016
Sadya Pal Dosaj	A.M.I. Coast Magnetics	5333 West Washington Boulevard Los Angeles, CA 90016
Larry W. Brashear	Basic Four Corporation	14101 Myford Road Tustin, CA 92680
John Gilbert	Beckman Institute	2500 Harbor Boulevard Fullerton, CA 92634
Leonard Pursiano	Bendix Corporation - Department 6401 Guidance Systems Division	Teterboro, NJ
H. Raymond Brown	Boeing Company	P.O. Box 3999 Seattle, WA 98124
Art Grunnell	D.B. Products	253 North Vinedo Pasadena, CA
Ernest H. Carlson, Jr.	Elnite Electronics	1730 21st Street Santa Monica, CA
John Klaarenduh	Ford Aeronutronic	Ford Road Newport Beach, CA 92660
Ralph A. Grassi	Ford Aerospace Communications	Ford Road Newport Beach, CA 92660
H.A. Lewis	Ford Aerospace Communications	Ford Road Newport Beach, CA 92660
J.A. Goudy	Ford Aerospace Communications	Ford Road Newport Beach, CA 92660
Theodore V. Fekula	Ford Aerospace and Communications Corporation	300 Renaissance Center P.O. Box 43342
John Schwillers	Ford Aerospace and Communications	Ford Road Newport Beach, CA 92660
Robert Hausmann	Ford Aerospace and Communications	Ford Road Newport Beach, CA 92660
Dale A. Davidson	General Dynamics Convair	P.O. Box 80847 San Diego, CA 92138 MZ 41-6260
San Poulakidas	General Dynamics Convair	2681 Pheasant Drive San Diego, CA 92123
A.T. Wells	General Dynamics Convair	P.O. Box 80847 San Diego, CA 92123 MZ 41-622-0
Floyd Allen	Harry Diamond Labs	2800 Powder Mill Road Adelphi, Ind. 20783

13.0 COST DATA ESTIMATES

Based on the information obtained from the demonstration of a continuous process, and other encapsulation investigations during the MM&T program, a brief cost analysis for representative mold configurations for the toroid transformer are given in Tables 13-1 through 13-5. Quantities are for low production, 100 parts/month; medium, 1000 parts/month and high, 10,000 parts/month. Labor in all cases is assumed to be \$25/hr. Other assumptions are noted on each table.

It is obvious that the major cost item is labor for all of the production systems. Labor was assumed the same straight across without taking into account any learning curve.

TABLE 13-1. COST ANALYSIS, SILICONE RUBBER MOLD,
LOW PRODUCTION RATE

100 parts/month = 5 parts/day				
Total Production Run				
Item	Cost	25	50	100
Make molds (5) Labor 6 hours Material \$12	\$42.00	\$ 8.40	\$ 4.20	\$ 2.10
Material Epon 825	\$18/gal.	1.00	1.00	1.00
Labor, 0.4 hour/mold	\$10.00	10.00	10.00	10.00
Total/Part		\$19.40	\$15.20	\$13.10
Assumptions:				
1. Fabrication of mold masters not included				
2. Molds will make 100 parts each				

TABLE 13-2. COST ANALYSIS, SILICON RUBBER MOLD,
MEDIUM PRODUCTION RATE

1000 parts/month = 50 parts/day					
Total Production Run		Cost Per Part			
Item	Cost	100	500	1000	5000
Make molds (50)					
Labor/mold 1.2 hours					
Material \$12.00/mold	\$42.00/mold	\$21.00	\$ 4.20	\$ 2.10	\$ 0.42
Material Epon 825	\$18/gal.	1.00	1.00	1.00	1.00
Labor, 0.4 hr/ mold	\$10.00	10.00	10.00	10.00	10.00
		\$32.00	\$15.20	\$13.10	\$11.42
Assumptions:					
1. Fabrication of mold masters not included					
2. Molds will make 100 parts each					

TABLE 13-3. COST ANALYSIS HIGH PRESSURE MOLD
LOW PRODUCTION RATE

100 parts/month = 5 parts/day					
Total Production Run		Cost Per Part			
Item	Cost	100	500	1000	5000
Molds (5)	\$200 each	\$10.00	\$ 2.00	\$ 1.00	\$.20
O Rings Replace after 10 parts	\$7/set	0.70	0.70	0.70	0.70
Material 55 cc/part	\$18/gal. qty disc	1.00	0.62	0.57	0.57
Labor 2 hr for 5 parts	\$50	10.00	10.00	10.00	10.00
Total Cost/Part		\$21.70	\$13.32	\$12.27	\$11.41
Assumptions:					
<ol style="list-style-type: none"> 1. Vacuum/pressure equipment capital expenditure 2. Labor includes cleanup, mold release, correction of mold to pressure/vacuum manifold, hand mixing assembly, disassembly 3. All material for production run bought at same time 4. Heating units not included 					

TABLE 13-4. COST ANALYSIS HIGH PRESSURE MOLD
MEDIUM PRODUCTION RATE

1000 parts/month = 50 parts/day					
Total Production Run		100	500	1000	5000
Item	Cost	Cost Per Part			
Mold (50)	\$100 each	\$50.00	\$10.00	\$ 5.00	\$ 1.00
"O" Rings Replace after 10 parts	\$7/set	0.70	0.70	0.70	0.70
Material 50 cc/part	\$18/gal qty disc	0.57	0.57	0.57	0.57
Labor, 8 hours/ 50 parts	\$200/ 50 parts	4.00	4.00	4.00	4.00
Total Cost/Part		\$55.27	\$15.27	\$10.27	\$ 6.27
Assumptions:					
<ol style="list-style-type: none"> 1. Vacuum/pressure equipment capital expenditure 2. Labor includes cleanup, mold prelease, correction of mold to pressure/vacuum manifold, hand mixing assembly, disassembly 3. Material Epon 825/HV hardener 4. Heating units not included. 					

TABLE 13-5. COST ANALYSIS, 6 CAVITY LIQUID INJECTION MOLD (LIM)

Total Production Run		10K	50K	100K
Item	Cost	Cost Per Part		
Mold Cavity Inserts (6)	\$1K/pair	\$0.60	\$0.12	\$0.06
Material	\$18/gal.	0.75	0.75	0.75
Labor	1 hr/cycle	4.16	4.16	4.16
Total/Part		\$5.51	\$5.03	\$4.97
Assumptions:				
<ol style="list-style-type: none"> 1. Cycle time, 35 min 2. 6 cavity mold 3. Continuous (24 hr) press operation would produce $6 \times 24 = 144$ parts/day 				

14.0 REFERENCES VOLUME II

- 14.1 ELEMENTS OF STRENGTH OF MATERIALS, TIMOSHENKO-MAC CULLOUGH, D. VAN NOSTRAND, NEW YORK, 1935, p. 18
- 14.2 A. BOUWERS AND P.G. CATH, "THE MAXIMUM ELECTRICAL FIELD FOR SEVERAL SIMPLE ELECTRODE CONFIGURATIONS," PHILIPS TECHNICAL REVIEW, VOL. 6, NO. 9, SEPTEMBER 1941, p. 270-278
- 14.3 Y SHIBUYA, ET AL, "VOID FORMATION AND ELECTRICAL BREAKDOWN IN EPOXY RESIN," IEEE TRANS ON POWER APPARATUS & SYSTEMS, VOL PAS-96 NO. 1 JAN/FEB 1977
- 14.4 MODERN PLASTICS ENCYCLOPEDIA, 1977.
- 14.5 ELECTRONIC DESIGN'S GOLD BOOK, VOL. I, p. 260, 1979 EDITION.
- 14.6 THOMAS REGISTER, 1979.
- 14.7 "LASER WIRE STRIPPING: EQUIPMENT AND OPERATION NOTES" INSULATION/CIRCUITS, VOL. 26, NO. 5, APRIL 1980, p. 47.

15.0 SPECIFICATIONS

MIL-F-14256

MIL-T-27D

MIL-I-16923G

MIL-S-23586C

MIL-STD-202E Method 101

Fed Test Method Std No. 406 Method 1083

Fed Test Method Std No. 406 Method 5011

JW 001177

NASA TND-8003

JSC 08962 Rev. R

ASTM D 149-75

ASTM D 150-74

ASTM D 257-76

ASTM D 570-63 (1972)

ASTM D 1002-72

ASTM D 2566-69 (1975)

ASTM E 595-77

HMS 16-1576

HMS 20-76

HMS 20-1699

HP 6-26

HP 16-92

HPR 40004

16.0 APPENDIX 1

16.1 HP 67/97 COMPUTER PROGRAMS

(Register entries section 8.3.1.)

16.1.1 Constant Encapsulant Diameter

001	f lbl A	31	25	11	Total Force P_w
002	STO		33	08	Wire dia
003	RCL 4		34	04	Thermal coef of expansion of encapsulant ϵ_e
004	ENTER			41	
005	RCL 3		34	03	Thermal coeff of expansion of wire ϵ_w
006	-			51	
007	RCL 1		34	01	Hi Temp T_2
008	ENTER			41	
009	RCL 2		34	02	Lo Temp T_1
010	-			51	
011	x			71	
012	$h\pi$		35	73	
013	x			71	
014	4			04	
015	+			81	
016	RCL 5		34	05	Wire Mod of Elasticity E_w
017	$h 1/x$		35	62	
018	RCL 8		34	08	
019	gx^2		32	54	

020	÷		81	
021	RCL 7	34	07	Encapsulant dia d_e
022	gx^2	32	54	
023	RCL 8	34	08	
024	gx^2	32	54	
025	—		51	
026	RCL 6	34	06	
027	x		71	
028	h 1/x	35	62	
029	+		61	
030	÷		81	
031	f FIX	31	23	
032	h RTN	35	22	
033	f lbl B	31 25	12	Calculate wire stress S_w in PSI
034	$h\pi$	35	73	
035	÷		81	
036	4		04	
037	x		71	
038	RCL 8	34	08	
039	gx^2	32	54	
040	÷		81	
041	h ENG	35	23	
042	h RTN	35	23	

16.1.2 Constant Encapsulant Thickness

001	f lbl	31 25	11	Total Force P_w
002	STO 8	33	08	Wire dia
003	RCL 4	34	04	Thermal Coeff of expansion of encapsulant ϵ_e
004	ENTER		41	
005	RCL 3	34	03	Thermal Coeff of expansion of wire ϵ_w
006	—		51	

007	RCL 1	34	01	Hi Temp T_2
008	ENTER		41	
009	RCL 2	34	02	Lo Temp T_1
010	-		51	
011	x		71	
012	$h\pi$	35	73	
013	x		71	
014	4		04	
015	\div		81	
016	RCL 5	34	05	Wire Mod of Elasticity E_w
017	$h \ 1/x$	35	62	
018	RCL 8	34	08	
019	gx^2	32	54	
020	+		81	
021	RCL 7	34	07	Encapsulant dia d_e
022	gx^2	32	54	
023	RCL 7	34	07	
024	Enter		41	
025	2		02	
026	x		71	
027	RCL 8	34	08	
028	x		71	
029	+		61	
030	RCL 6	34	06	
031	x		71	
032	$1/x$	35	62	
033	+		61	
034	+		81	
035	$h \ RTN$	35	22	
036	f lb1 B 31	25	12	Calculate wire stress S_w in PSI
037	$h\pi$	35	73	
038	\div		81	
039	4		04	
040	x		71	

041	RCL 8	34	08
042	gx ²	32	54
043	÷		81
044	h ENG	35	23
045	h RTN	35	23

16.2 COMMERCIAL CONCERNS CONTRIBUTING MATERIALS, INFORMATION, AND/OR EXPERTISE TO MM&T PROGRAM

a. Magnetics Vendors

AMI/Cost Magnetics
5333 W. Washington Blvd.
Los Angeles, CA 90016
Attn: Mr. Satya Dosaj, Chief Engineer

OECO
712 South East Hawthorne
Portland, OR 97214
Attn: Mr. Steve Meek, Vice President

Robert M. Hadley Co.
750 W. 51st St.
Los Angeles, CA 90765
Attn: Mr. Charles Hadley, Sales Manager

b. Metering - Mixing Equipment

Accumetric Rep.
Southerland & Associates
3123 Glendon Ave.
Los Angeles, CA 90034
Attn: Mr. Arnold Sutherland

Graco Inc.
3165 So. Garfield Ave.
Los Angeles, CA 90040

c. Horizontal LIM Mold

Hull Corporation
Hatboro, PA 19040
Attn: Mr. Jack MacInnes

d. Laser Welding

Coherent Radiation, Inc.
3210 Porter
Palo Alto, CA

Compulaser, Inc.
6733 Eton Ave.
Canoga Park, CA

e. Premix-Frozen Encapsulants

Ablestik Labs
833 W. 182 St.
Gardena, CA

Products Research & Chemical Corp.
5430 San Fernando Rd.
Glendale, CA

f. Encapsulant Material Suppliers

<u>Material</u>	<u>Manufacturer</u>
Eccoseal 63, W-67 1207, 1218 Stycast 62	Emerson & Cumming, Inc. Dielectric Materials Division Canton, Mass. 02021
Conathane: EN-2, EN-9(OZR) EN-9, EN-10, EN-11 Conepoxy: Y 1000/07, IM 1145 RN 1600	Conap Incorporated 1405 Buffalo St. Olean, New York 14760
RTV: 11/DBT, 60/DBT 8111, 615, 619, 627, 655, 670	Silicone Products Department General Electric Company Waterford, New York 12188
GE: 702, 707	Insulating Materials Department General Electric Company One Campbell Road Schenectady, New York 91749
Scotchcast: 235, 255 280, 281, 5237	3 M Company Industrial Electrical Products Division 3 M Center Saint Paul, MN 55101
D 230, D 400, T 403	Jefferson Chemical Company P.O. Box 430 Bellaire, Texas 77401

<u>Material</u>	<u>Manufacturer</u>
Hysol C 15-015 C 60 HD 3561	Hysol Division The Dexter Corporation 15051 E. Don Julian Road Industry, CA 91749
Epocast: 202, 204A/9816 204A/9652 Uralane 5753	M & T Chemicals, Incorporated Furane Products Division 5121 San Fernando Road West Los Angeles, CA 90039
Epon 825/HV RFC825	E. V. Roberts & Associates Division EVRA Incorporated P.O. Box 868 Culver City, CA 90230

g. High Resistance Paints

Hugheson Chemical Co.
Erie, PA 16512

h. Air-Abrasive Equipment

Pennwalt Corp., Wallace & Tiernan, Inc.
S.S. White Industrial Products Division
25 Main St.
Belleville, NJ 07109

Secana Co.
613 Justin Ave.
Glendale, CA